

Proceedings of:

Micrometer-Tolerance Assembly of Macroscopic Structures

1995 Spring Topical Meeting

April 4-7, 1995

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The American Society for Precision Engineering (ASPE) is a multidisciplinary professional and technical society concerned with research and development, design, manufacture and measurement of high accuracy components and systems. ASPE activities encompass relevant aspects of mechanical, electronic, optical and production engineering, physics, chemistry, and computer and materials science. Membership is open to anyone interested in any aspect of precision engineering.

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Preface

This book comprises the proceedings of the 1995 Spring Topical Meeting. The contributions reflect the authors' opinions and are published as presented to ASPE, without change. Their inclusion in this publication does not necessarily constitute endorsement by the ASPE, or its editorial staff.

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1995 Spring Topical Meeting

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1995 Spring Topical Meeting

Meeting Schedule

Tuesday, April 4		Wednesday, April 5	Thursday, April 6	Friday, April 7	
	7:30	CONTINENTAL BREAKFAST			
	8:30	REGISTRATION			
	9:00	OPENING SESSION	INVITED LECTURES V	TECHNICAL SESSION II	
	9:15				
	10:00	INVITED LECTURES I	BREAK		
	10:30		INVITED LECTURES VI	BREAK	
	10:45	BREAK			
	11:00	INVITED LECTURES II		OPEN FORUM	
	12:00		LUNCH	CLOSE OF CONFERENCE	
	12:30	LUNCH			
	1:00		INVITED LECTURES VII		
	1:30	INVITED LECTURES III			
	3:00	BREAK	BREAK		
	3:30	INVITED LECTURES IV	TECHNICAL SESSION I		
	5:00				
ON-SITE REGISTRATION AND REFRESHMENTS	6:30	REFRESHMENTS			
	7:30	DINNER			
	8:30	REVIEW & DISCUSSION REFRESHMENTS			
	9:30				

Foreword

The 1995 ASPE Spring Topical Meeting covers four major themes related to manufacturing macroscopic structures that require micrometer-tolerance assembly and arrangement of high-precision parts: (1) design, specification, and tolerancing, (2) manufacturing, (3) inspection and qualification, and (4) assembly. Cross-cutting these four themes, the meeting focuses on the processes, methods, instrumentation, and measurements which have been developed to achieve economic and efficient manufacture of such structures. Examples of products included: air-bearings, CRTs, dies and molds, fiber-optic components, mask aligners, miniature analytical instruments, magnetic disk drives, precision optics, piezo-electric and magneto-strictive motors, and steppers.

The meeting was organized to bring together specialists from these diverse product areas and to provide a forum for the exchange of ideas about state-of-the-art assembly approaches, to identify common supporting technologies, and to pinpoint the "show-stoppers" as tolerances are tightened and part sizes decrease. The organizers hope that each attendee will leave the meeting with interesting and potentially beneficial ideas about how to solve some of his/her problems as well as some new challenging issues to think about.

Each of the authors was asked to present both a status-like report of their subject and a good indication of the real problems that they currently face in their work. The subject matter, therefore, deals closely with areas at the forefront of most of the individuals' and companies' research and development of manufacturing. Because of this, and in keeping with the spirit of informality of these topical meetings, we request that the individual authors be contacted prior to quoting results reported in the abstracts in this volume.

The Organizers of the 1995 Spring Topical Meeting

*Clayton Teague, National Institute of Standards and Technology
Alan Feinerman, University of Illinois at Chicago
John Bruning, Tropel Corporation
Don Lucca, Oklahoma State University
George Platt, Texas Instruments
Jay Raja, University of North Carolina at Charlotte
Sheldon Schultz, University of California at San Diego*

Technical Paper Index

Opening Session

Wednesday, April 5, 9:00 a.m.

Welcome and Introductions — E. Clayton Teague and Alan Feinerman

Conference Outline and Goals — E. Clayton Teague

Invited Lectures I

Wednesday, April 5, 9:15 - 10:45 a.m.

1. **Design, Specification and Tolerancing of Micrometer-Tolerance Assemblies**
Dennis A. Swyt (National Institute of Standards and Technology) page 3
2. **A Structured Approach to Precise Assembly of Lithographic Lenses**
John H. Bruning (Tropel Corporation) page 7

Invited Lectures II

Wednesday, April 5, 11:00 a.m. - 12:30 p.m.

1. **Precision Fabrication of Analytical Instruments**
Alan D. Feinerman (University of Illinois at Chicago) page 9
2. **Five Degrees of Freedom Scanning Test Stand for Magnetic Read/Write Heads with 1 nm Resolution***
Sheldon Schultz (University of California at San Diego)

Invited Lectures III

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John P. Schaefer and Lyale Marr (Texas Instruments, Inc.) page 13
2. **The Deformation and Registration of a Foil Membrane in an Interchangeable Assembly Process***
Paul Strauss (Zenith Electronics) page 17

Invited Lectures IV

Wednesday, April 5, 3:30 - 5:00 p.m.

1. **Dimensional Variability of Steel Castings***
F. E. Peters, R. C. Voigt and E. C. De Meter (The Pennsylvania State University) and Malcomb Blair
(Steel Founders Society of America) page 18
2. **Flatness, Parallelism and Other Novel Uses of Grazing-Incidence Interferometry in Precision Engineering**
Louis Denes (Tropel Corporation) and James Salsbury (Cummins Engine Company) page 20

Invited Lectures V

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1. **Fabrication of Fiber Bundle Arrays for Free-space Photonic Switching Systems***
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and Stephen J. Hinterlong (AT&T Bell Laboratories) page 24
2. **Aligning and Low Temperature Bonding of Multiple Integrated Circuits***
Robert Bower (University of California at Davis) page 25

Invited Lectures VI

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1. **Diesel Injector Precision Engineering***
Marion B. Grant, Wayne A. Eckerle, Gary A. Garitson, and Michael L. Molnar
(Cummins Engine Company) page 27
2. **Evolution in the Requirements for Surface and Form Measurement***
Alex Tabenkin and Duane Christy (Federal Products Co.) page 28

Invited Lectures VII

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Richard F. Carson (Sandia National Laboratory) page 29
2. **Micron-size Milling Tools: Fabrication and Use**
Michael J. Vasile and Craig R. Friedrich (Louisiana Tech University) page 30

Technical Session I

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Richard L. Rhorer (Los Alamos National Laboratory) page 34
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Peter V. Pistecky (Delft University of Technology) page 38
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David H. Youden (Rank Pneumo Inc.) page 42

Technical Session II

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Boyd M. Evans III, Slobodan Rajic and Joseph P. Cunningham (Oak Ridge National Laboratory) page 46
2. **The Grating Array: Sub-micrometers Control in Five Degrees of Freedom**
Anthony E. Gee (Cranfield University, UK) page 50
3. **Determination of Anisotropy in the In-Plane Radial Residual Stresses of 100 mm Diameter (100) P-Type Silicon Wafers by Shadow Moiré Interferometry and Finite Element Analysis**
K. Ghaffari, B. Wang, D. McDowell and S. Danyluk (Georgia Institute of Technology) and M. Billone
(Argonne National Laboratory) page 54
4. **Part Transfer in Ultraprecision Machining Processes***
Richard L. Rhorer (Los Alamos National Laboratory) page 57

Multi-dimension Inspection Technology in Quality Management**

Shuguang Jin, Zhixiang Chen (Huazhong University of Science & Technology) and Zhang Wu
(Nanyang Technological University) page 58

Open Forum

Friday, April 7, 11:00 a.m. - 12:00 p.m.

* Extended abstract not available at press time.

** Author unable to attend the meeting.

Technical Papers



A S P E

Design, Specification and Tolerancing of Micrometer-Tolerance Assemblies

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Introduction

An increasing number of economically important products manufactured by U.S. companies are comprised of assemblies of macroscopic parts with microscopic tolerances. The dimensions of these component parts range from a few to a few hundreds of millimeters in size. The tolerances or acceptable deviations from those dimensions are of the order of micrometers. Such micrometer-tolerance assemblies include not only electronic products and hybrid electronic-mechanical products, but, less expected, a number of purely mechanical devices. Thus micrometer-tolerance assemblies include not only integrated-circuit devices and magnetic-memory read-write heads, but automobile-engine systems, including fuel injectors, hydraulic valve lifters and even piston and cylinder assemblies. Focusing on these, this paper: 1) reports examples of micrometer-tolerance assemblies; 2) discusses strategies in design, specification and tolerancing (DS&T) which some companies have adopted for the manufacture of such assemblies; and 3) identifies generic-technology, measurement and standards issues in DS&T associated with that manufacture.

Scope, Challenge and View of Micrometer-Tolerance Assemblies

Some modern products comprised of micrometer-tolerance assemblies include in decreasing order of size: hydraulic systems of heavy equipment with 300 mm-long cylindrical elements having geometric tolerances of $\pm 1\text{--}3\text{ }\mu\text{m}$; automobile engine pistons and cylinders with overall tolerances of the order of typically $7.5\text{--}10\text{ }\mu\text{m}$ with size-class tolerances of typically $1.5\text{ }\mu\text{m}$; and fuel-injector plunger-bore assemblies with form tolerances of less than $\pm 1\text{ }\mu\text{m}$ and size-class tolerances of $\pm 0.5\text{ }\mu\text{m}$. Also in this range of interest are suspensions of magnetic-memory read-write heads, which have parts which are millimeters in size having sub-micrometer tolerances.

One of the challenges in manufacture of micrometer-tolerance assemblies is the degree of temperature control required for manufacture of macroscopic-size parts to $1\text{ }\mu\text{m}$ -level tolerances. For example, for the thermal variation in size of a 100 mm steel part to represent less than 10% of a $1\text{ }\mu\text{m}$ part tolerance, a temperature control of better than $0.1\text{ }^{\circ}\text{C}$ is required.

Another challenge is that, in terms of quality and difficulty of manufacture, micrometer-tolerance assemblies correspond to the highest tolerance grade specified in the current standard on tolerancing for fit. For example, components with dimensions and tolerances respectively of 300 mm and $2.5\text{ }\mu\text{m}$, 100 mm and $1.5\text{ }\mu\text{m}$, and 10 mm and $0.5\text{ }\mu\text{m}$ each belong to International Tolerance Grade 1 [1,2]. This to say that many of today's mass-produced goods have tolerances corresponding to those of carefully crafted master gages of the near past. This remarkable fact can be understood in terms of a reported trend in tolerances on manufactured goods. According to this trend, tolerances on manufactured products have been tightening, that is, decreasing in magnitude, at an average rate of approximately a factor of ten every twenty years [3,4].

An effective means for manufacturers to deal with such challenges in the manufacture of micrometer-tolerance assemblies is to consider in their DS&T all the stages of the product cycle - design, component, assembly and end-product.

Strategies for DS&T of Micrometer Tolerance Assemblies

Within a the combustion system alone of a modern multi-valve automobile engine are four examples of micrometer-tolerance assemblies with dimensions and tolerances of the "master-gage" tolerance grade. These are: the fuel-injector plunger and bore assembly; the valve lash adjuster assembly; the piston, rod, and wrist pin assembly; and the piston and cylinder assembly. In the DS&T of these assemblies, the dominant strategy has been what is variously called the size-and-sort, size-selective or size-classification method of assembly. Representing a trend for the auto industry as a whole, individual car companies have been evolving from multiple- to single-size class assembly for piston-rod. Over the last two decades, this evolution is taking the form of progressive tightening of tolerances on, for example, engine pistons from as much as 20 μm down to as little as 1.5 μm , with a progressive decrease in the number of size classifications from as many as thirteen to as few as one.

As practiced within major U.S. car companies, the choice of multiple- versus single-size classes and tighter versus looser tolerances is strategic with the basis for the choice being a front-end consideration of the functional dependence of tighter or looser tolerances each stage. This begins with the last stage, which is customer use. Thus the design considerations include: the performance, reliability, cost and availability of the assembled system; the ease of assembly of those components; and their ease of manufacture. A part of this basis for making engineering trade-offs among such variables is use of Taguchi's design-of-experiment approach. The approach aims to achieve "robust design", in this case of engine characteristics, where target values of engine component dimensions are set at the looser-tolerance end of a "flat" region of the customer-perceived quality loss function. A tool used to support this approach and allows a search for flat spots in the quality loss function is "variation simulation analysis." VSA is a software for quantitative analysis of the effects of dimensions and tolerances on assemblability and functionality [5, 6].

Issues in DS&T of Micrometer-Tolerance Assemblies

There are a number of generic technology, measurement and standards issues in the DS&T of micrometer-tolerance assemblies at the various stages of the product cycle.

Issues of DS&T at the Design Stage Associated with the computerization of the entire product cycle are issues of non-interoperability of commercial DS&T software systems. Such systems include those for CAD, solid modelling, finite element analysis, tolerance stacking, and assembly simulation. Another problem is the need for ambiguity-free representation and interpretation of design. This latter problem is being addressed in part by two new tolerancing standards [7,8]. Still-to-be-addressed are two related problems: that of representing and assessing cylindricity, a geometric feature critical to DS&T of micrometer-tolerance assemblies; and that of determining measurement uncertainty of point-sample measuring systems, such as coordinate measuring machines, used in the assessment of geometrical features, including cylindricity.

Issues of DS&T at the Component-Fabrication Stage Among the most basic issues in DS&T of micrometer-tolerance assemblies at the component stage is that of being able to achieve micrometer tolerances on components at the volumes of production upon which economic viability depend. Specific instances where there are such limitations in fabrication capabilities include the speed of precision grinding, understanding of ceramic-grinding processes, and reproducibility of injection-molding operations.

Issues in DS&T at the Component-Measurement Stage Also among the issues in DS&T of micrometer-tolerance assemblies at the component stage is the need for higher-accuracy higher-speed measurements of three-dimensional form. Specific measurement needs include those for: greater accuracy per se in the measurement of form of long, e.g. 300 mm, micrometer-tolerance cylinders; the need for high-speed 0.1 μm uncertainty

measurements on small cylinders; and the need for massively-parallel, yet accurate, point-sample measurement of complex forms, such as those of jet-engine turbine blades and automobile transmission gears..

Issues in DS&T at the Assembly Test Stage A major issue of DS&T at the assembly stage of production of micrometer-tolerance assemblies which that bears on design, specification and tolerancing is the current inability to automate the assembly of various micrometer-tolerance components to the degree sought for large-volume production. Application-specific issues include the need for: higher-precision angular alignment for automated insertion of high-aspect-ratio components; special part handling such as for automobile pistons, where there is a need to compress the rings and precisely align piston-ring subassemblies for insertion; and carrying out insertions for assembly fits with sub-micrometer tolerances.

Issues in DS&T at the Final Product Stage A new issue of DS&T for the final stage of the product cycle of micrometer-tolerance assemblies is the growing need to be a formally qualified supplier. This may involve demonstrating conformity to the customer's own supplier-certification system (as in the auto industry), to ISO-9000 (as in industry in general), or to a new concept being proposed, "Geometric Product Specification" [9]. Under a GPS system, an engineering drawing would need to carry specifications referring documentary standards governing each of six aspects of DS&T. This "chain of standards" would explicitly define: the formal standards governing each of six aspects of DS&T. This "chain of standards" would explicitly define: the formal symbols of product documentation; the theoretical definition of tolerances on ideal features; the descriptive-parametric definitions of real non-ideal features; the detailed rules for comparing measurement results with tolerance limits to decide upon accepting or rejecting the workpiece; the performance characteristics of the specific measuring equipment, including hardware and software, used to measure the actual features; and the requirements on the calibration standards and procedures for the measurement equipment used to assure conformity of manufactured components to tolerances.

Conclusion

Many economically vital U.S. products are comprised of assemblies with components toleranced at the micrometer level. Such tolerances place assemblies at or beyond the limits of what is attainable with fully interchangeable parts. As a result, the design, specification and tolerancing of such assemblies requires special care. A major aspect of this care is taking into problems associated with design, specification and tolerancing which arise at each stage of the product cycle. Major advances in technology, especially computerization, have been sources both of new capabilities and new problems at virtually every stage of the cycle. While proprietary concerns are a dominant consideration in how such problems are attacked, many of the problems have generic technology, measurements and standards aspects which those working on such matters can help address.

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A STRUCTURED APPROACH TO PRECISE ASSEMBLY OF LITHOGRAPHIC LENSES

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The design and assembly of lenses for microlithography requires state-of-the-art methods and materials to achieve the remarkably challenging requirements needed to print the complex micro-circuit patterns of integrated circuits. The optical requirements are so stringent that present or foreseeable optical manufacturing technologies for glass and metal components are inadequate to assure success without elaborate in-process measurements and corrections.

Modern lithographic lenses weigh more than 200 Kg, are nearly a meter in length and are valued at greater than \$1M. Such lenses can image features as small as $0.25\text{ }\mu\text{m}$ over an image field diameter of 31 mm and will likely be used to print 256 Megabit memory devices (DRAM's). These lenses contain more than 20 lens elements whose more than 40 surfaces must be accurate in form to a few nm over apertures of up to 250 mm in diameter. This accuracy is required to mitigate the inevitable buildup of optical path length errors for light passing through so many elements. Such tolerances are substantially tighter than what is required for a lens be "diffraction-limited." The diffraction limited condition requires that the peak-to-valley optical path length difference (OPD) between any two rays passing through the optical system be less than 0.25 of the wavelength of operation. This condition implies that a minimum of 84% of the energy from a point source is contained within the central diffraction spot. In this case, the "Strehl-ratio" is 0.84.

The semiconductor manufacturing process has very rigorous manufacturing design requirements which dictate the strict lens design specifications and manufacturing process. These requirements usually drive the Strehl-ratio specification to exceed 0.95. Most of the lens designer's effort is directed to minimizing the OPD over an image plane which must be flat to $<0.10\text{ }\mu\text{m}$. In dimensional terms, all rays traveling from the mask to the wafer travel an optical path length of about 1 meter and must be equal in path length within 30-40 nm or 30 ppb. This requires an optical glass homogeneity specification for the index of refraction of $<0.5\text{ ppm}$.

Equally demanding is the requirement that the image acuity and, more importantly, the image of the line widths be uniform over the image field of the lens to within a few percent. Image placement accuracy (or lens distortion) must be within 30-40 nm over the full image field diameter of 31 mm or 1 ppm.

The manufacturing processes which go into making such lenses must be reproducible such that multiple copies of such lenses can be made at a tolerable cost and be indistinguishable from one another in performance in production. None of this would be possible without the use of interferometry as an integral part of the manufacturing process and without the use of a highly structured manufacturing processes. There are simply too many opportunities for every step of the manufacturing process to lead to a critical defect which may not be detected until very late in the manufacturing process.

Because of the extreme tolerances, there need to be in-process assembly methods which can compensate for the inevitable buildup of errors. We will describe many of the methods used in the design of the lens, tolerancing of the glass and metal and assembly of the components. Every degree of freedom in the assembly process is used to advantage to optimize performance of the finished lens. For example, lithographic lens elements usually have a (relatively large) tolerance in axial position of 5-10 μm , since a small error in position of one element, if known, can usually be compensated for by repositioning one or more of the remaining elements in the stack. Element tolerances are such that elements must be fabricated, tested and mounted in the same orientation to gravity in which they will ultimately be used. Elements usually have a centering tolerance of 0.5-5.0 micrometers.

Finished elements are measured with surface interferometry and fit to 3-dimensional polynomial surfaces which, together with the thickness, are modeled for the remaining degrees of freedom which include air-spaces and angular orientation. By proper exploitation of all degrees of freedom during the manufacturing process, these high accuracy lenses can be made to the required accuracy and in volume.

Precision Fabrication of Analytical Instruments

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The application of semiconductor processing and fiber optic technology to manufacturing has given us the capability to generate mm³ and larger objects consisting of metals, semiconductors, polymers, and insulators with ~1 μm accuracy. This technology has been applied to the miniaturization of low and medium voltage scanning electron microscopes (SEMs). Electron optical calculations indicate that a 15kV SEM 8.5mm long will have a 2.2nm resolution at a 1mm working distance. A 2.5kV SEM 3.2mm long will have a 3.8nm resolution at a 0.5mm working distance. These miniature SEMs will be easier to use since each critical component, such as charged particle sources, lenses, deflectors, and detectors will be permanently aligned to the optical axis. This technology is also being developed to produce a 5 meter long 120 GHz linear accelerator to produce 50 MeV electrons and an integrated undulator to produce hard x-rays.

1. Fabrication

A (100) silicon wafer is anisotropically etched to create an aperture and four orthogonal v-grooves on both surfaces of a silicon die. Precision pyrex fibers align and bond the v-grooves on the top of one silicon die to the bottom of the next die as shown in Figure 1, this process will be referred to as "stacking". The processing details to stack a single Einzel lens and the relationship between v-groove width, fiber diameter, and separation between die were previously described[1] and will only be summarized here. Four masks were used to fabricate the Einzel lens: a top nitride mask with $270 \times 7000 \mu\text{m}^2$ openings, a bottom nitride mask with $270 \times 7000 \mu\text{m}^2$ and $1500 \mu\text{m}$ square openings, an aperture mask with circular openings ranging from 10 to $200 \mu\text{m}$ in diameter, and a bottom oxide mask with $2000 \mu\text{m}$ square openings. A silicon nitride layer was deposited on the wafers and rectangular openings were etched in the nitride after aligning the mask to the $\langle 110 \rangle$ direction. The bottom surface of the wafer was then patterned with the bottom nitride mask after an infrared alignment using etched

features in the nitride on the top of the wafer. An aluminum film was deposited on the top of the wafer and patterned with the aperture mask and silicon was removed in a reactive ion etcher. As shown in Figure 1, a deeper anisotropic etch ($\sim 381\mu\text{m}$) is required to etch through the silicon wafer to expose an aperture than when etching a v-groove to seat a pyrex optical fiber. In order to avoid overetching the v-grooves or etching the apertures the wafers were oxidized in a steam ambient to grow $2\mu\text{m}$ of SiO_2 in the openings in the nitride layer. This oxide was removed with buffered HF acid for the aperture etch but not over the v-grooves with the bottom oxide mask. The oxide etch removes a negligible amount of nitride. The wafers were then anisotropically etched in 44% by weight KOH in H_2O at 85°C . The wafers were kept in this solution for 3.7 hours until the KOH solution etched partially through the wafer. The oxide preventing the v-grooves from being etched was removed and the wafers reinserted into the KOH bath for an additional 1.7 hours. The $1500\mu\text{m}$ square openings would have etched through the $381\mu\text{m}$ thick silicon wafer but the wafers were removed once the apertures became visible from the bottom of the wafer.

The $270 \times 7000\mu\text{m}^2$ openings form partially etched v-grooves $120\mu\text{m}$ deep to seat the $308\mu\text{m}$ diameter fibers. Wafers were expected to be stronger with truncated v-grooves. The nitride film was then removed with a 10 minute immersion in 49% HF acid followed by a deionized H_2O rinse. The wafers were then cut into $10 \times 12\text{mm}^2$ die and cleaned. The die were aligned and anodically bonded together with $308\mu\text{m}$ duran fibers. Duran or pyrex are chosen because their thermal expansion coefficients of $32 \times 10^{-7}/^\circ\text{C}$ closely match that of silicon at $26 \times 10^{-7}/^\circ\text{C}$. Both glasses have nearly identical chemical composition and are trademarks of Schott and Corning respectively. A second advantage is that the glasses can be attached to silicon at 250°C with a bond strength of 350psi. The $270\mu\text{m}$ v-grooves widened during the anisotropic etch to $280\mu\text{m}$ and the gap between the wafers is $138\mu\text{m}$.

As seen in Figure 1 stacking can extend structures in the vertical direction by increasing the number of layers and by using thicker silicon wafers and optical fibers. The accuracy between die is $1\text{-}3\mu\text{m}$ while the accuracy of aligning features on the top and bottom surface of a single die is $2\text{-}5\mu\text{m}$.

2. Horizontal stacking

Stacking can be used to extend structures in the horizontal direction as well as the vertical, as shown in Figure 2. Silicon die have been stacked by staggering the die by about half their length. This technique will allow us to build a linear accelerator 5 meters long. The assembled structure will have to be bonded to a precision surface.

3. Accuracy

The overall accuracy of a stacked structure depends on the accuracy of several factors including: the accuracy with which v-grooves can be etched, fiber diameter uniformity, wafer's total thickness variation (TTV) and surface flatness or total indicated runout (TIR), alignment of wafer's normal and flat to the $\langle 100 \rangle$ and $\langle 110 \rangle$ directions respectively, and the alignment of features on the top of a wafer to features on the bottom. The total indicated runout (TIR) or maximum surface deviation on an etched v-groove (111) surface is less than $1\mu\text{m}$. Fibers drawn with laser micrometer control have a $1\mu\text{m}$ or better tolerance on their diameter. The TTV and TIR for a 1cm^2 die is less than $1\mu\text{m}$. These defects would either be measured and compensated for with lithography or wafers would be purchased with tighter specifications. A standard wafer's normal is specified to 1° with respect to the $\langle 100 \rangle$ direction but it is possible to tighten this specification to 5×10^{-4} radians. A wafer's flat indicates the $\langle 110 \rangle$ direction to 0.5° but by cleaving the wafer the uncertainty is reduced to 10^{-4} radians. Another source of error is in the infrared alignment of features on the front surface of the wafer to features on the back of the wafer, $5\mu\text{m}$. This will be reduced in the future by etching a feature through the wafer. The alignment between layers by fibers is $\sim 1\mu\text{m}$. It is expected that the cumulative effect of these errors can be reduced to $1\text{-}3\mu\text{m}$.

3. CONCLUSIONS

A technique has been developed for creating deep and long three dimensional structures consisting of insulators, semiconductors, and metals. The technique combines semiconductor processing and fiber optic technology. These methods are being used to fabricate a low voltage miniature SEM and a linear accelerator.

4. ACKNOWLEDGMENTS

This research was supported by NIST contract No. 50SBNB3C7759 funded by ARPA.

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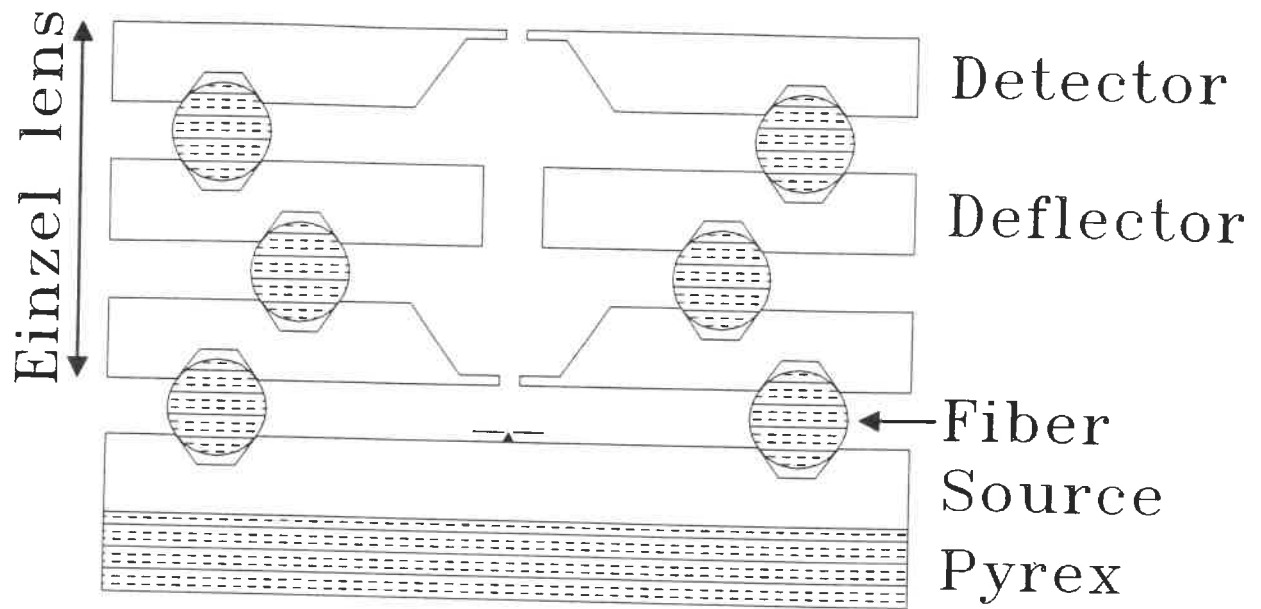


Figure 1

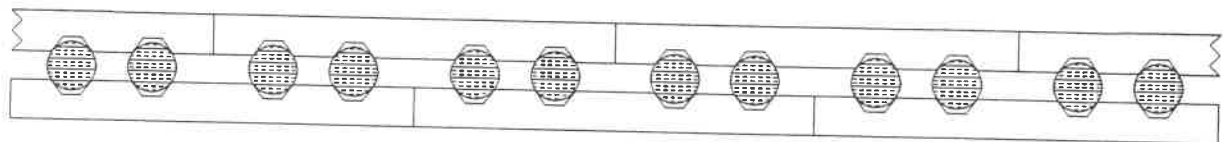


Figure 2

Figure 1 - Stacked MSEM

Silicon die are stacked with glass fibers that align and bond to the dies' v-grooves. The v-grooves are staggered to increase the die strength. The top and bottom surfaces of each die are optically aligned during fabrication. Each column consists of a micromachined field emission electron source and gate electrode, an Einzel lens that accelerates and focuses the emitted electrons, and a deflector.

Figure 2 - Stacked accelerator

Silicon die are stacked horizontally. LIGA (not shown) will be used to make the accelerating cavities.

Design and Fabrication Techniques for Precision Metal Mirror Assemblies: A Case Study

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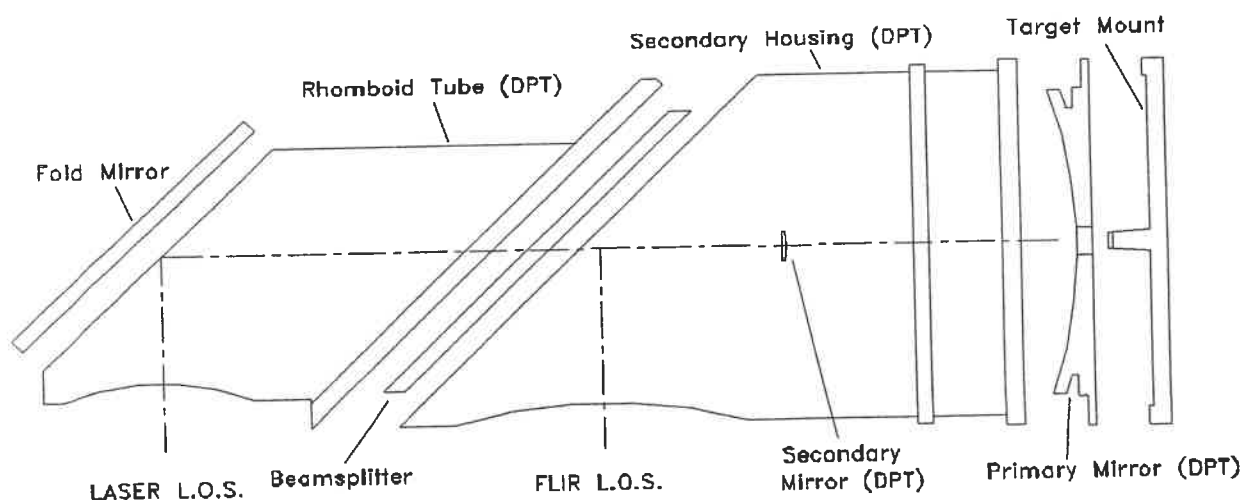
Introduction

The process of designing, fabricating, assembling, and testing precision metal mirror optical assemblies is a very detailed and exacting process which requires several engineering disciplines. This process is one which is not well understood by outside observers and is only partially understood by the various engineering groups involved in parts of the entire process. This paper will attempt to bring an understanding to the entire process by focusing on a sub-assembly of a TI electro-optics system which was designed, built, and delivered per contract over the past twelve months. In particular, special attention will be given to the numerous areas of concurrent engineering which ultimately affect the cost and performance of the final optical assembly as well as some of the innovative design and fabrication methods used to meet the aggressive delivery cycle.

System Description and Performance Criteria

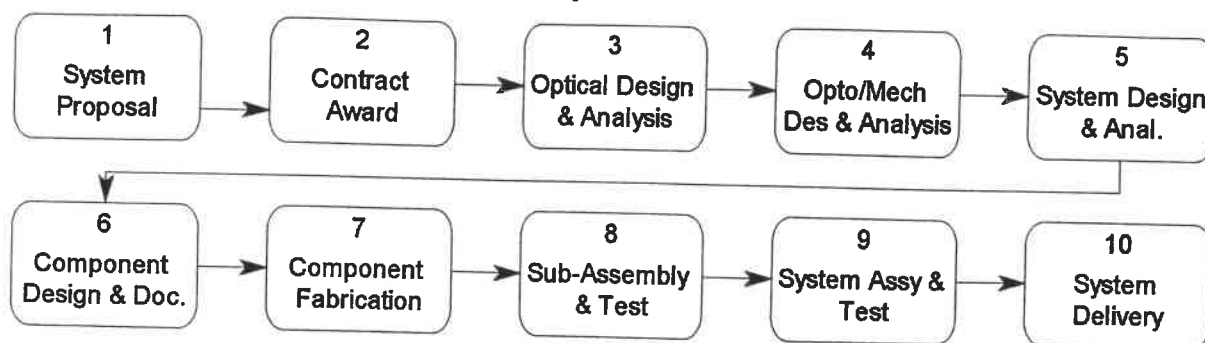
The Light Airborne System (LAMPS) Forward Looking Infrared (FLIR) set provides passive surveillance, identification, and designation of tactical targets during day or night and in adverse weather. Initial procurements are slated for deployment on the Navy's SH-60B and HH-60H helicopters. TI's FLIR system utilizes a second-generation infrared focal plane array with a Laser Rangefinder/Designator (LRD) to provide the capability to detect, track, and designate targets for laser guided munitions. The IR Receiver and LRD are mounted in a precision gimbal structure. External to this gimbal, a Boresight Module provides a common spatial reference for aligning the IR and LRD line-of-sight thereby assuring long range target designation capability. This paper will focus on the Boresight Module which uses DPT Snap-Together concepts along with conventional metal to glass mounting techniques to achieve the required alignments.

Boresight Module Assembly Layout



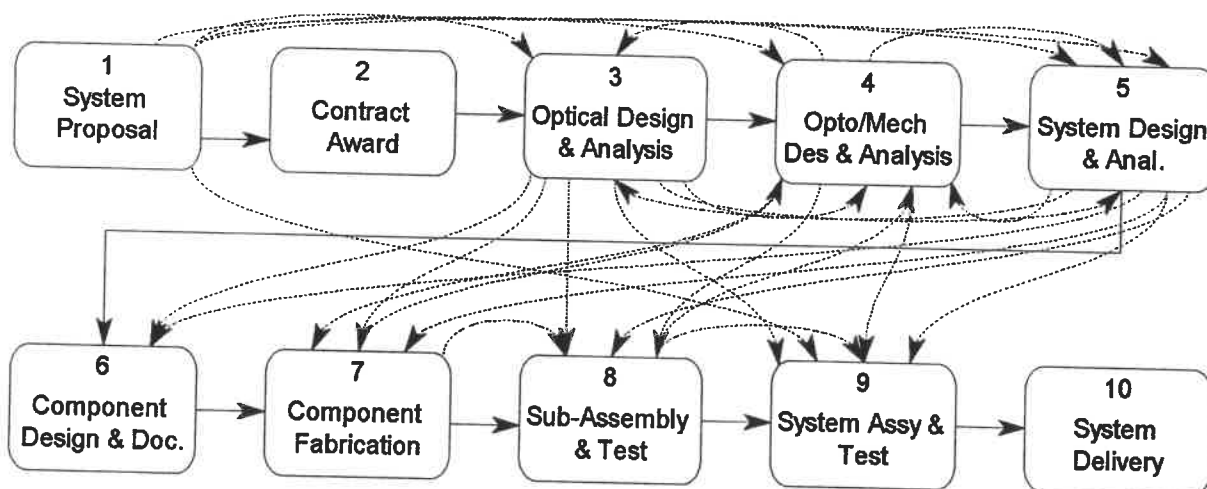
System Design, Fabrication, and Test Process

Flow Chart 1: System Design, Fabrication, and Test - Top Level



The top level flow chart shown is fairly simple and easy to understand. It shows a process where one step is completed and passed along to the next but in reality this is far from an accurate depiction of what really takes place. The complexity of an electro-optical system does not allow for each of the process steps to take place in a vacuum and the most successful programs are laden with a tremendous amount of interaction among the various engineers. This form of engineering interaction is called concurrent engineering which is described as 'concurring' with other engineers along the process flow to ensure that informed decisions are made at each step with regards to performance, producibility and ultimately cost. If one were to try to diagram the actual process in terms of interaction activities, the top level flow chart would look something this;

Flow Chart 2: System Design, Fabrication, and Test - Top Level with concurrent engineering interactions



As you can see from the number of interactions between stages 3, 4, and 5, these three areas are usually carried out simultaneously with multiple trade-off analysis and alternative design analyses. Below is an engineering concurrency matrix showing the various engineering disciplines and their typical interactions during the execution of a contract to deliver an electro-optics system. For the purpose of this paper, all engineering interactions are shown in terms of mechanical issues although a similar concurrent engineering process is followed on the electrical side of the system.

Table 1: Engineering Concurrency Matrix

Stage	Process Description	Engineer	Primary Issues and Concerns	Engineering Concurrency Matrix							
				Sys Eng	Opt Des	Opto-ME	Lead ME	Fab Pro	Proj ME	Mfg Eng	Test Eng
1	System Proposal	Sr. Sys Eng	Boresight, Range, Resolution, Environment, Size.	n/a	X	X	X			X	X
3	Optical Design & Analysis	Optical Eng.	Boresight, Range, Resolution, Environment, MTF, Size	X	n/a	X	X	X			X
4	OptoMech Des & Analysis	OptoMech Eng.	Thermal, Structural, Vib, Packaging, Mounting, Assy		X	n/a	X	X	X		X
5	System Design & Analysis	Sys Eng/Lead ME	Thermal, Structural, Sys Interface, Env. Testing, Assy	X	X	X	X	X	X	X	X
6	Component Design & Doc	Project ME	Form, Fit, Function, Assembly, Producibility, Cost, Yield			X	X	X	n/a	X	
7	Component Fabrication	Proj ME/Fab Prod	Cost, Yield, Producibility, Tooling, Delivery, Cycle Time					X	X	X	
8	Sub Assy & Test	Project ME	Methods, Fixtures, Processes, Performance vs. Spec			X	X	X	n/a	X	X
9	System Assy & Test	Lead ME	System Perf vs. Spec, Environmental, Vib Testing	X		X	n/a		X	X	X

The Concurrent Engineering Decision Process

Example No. 1: Component Breakout

Once the optical design is complete and is determined to meet the necessary performance criteria with-in the given constraints of size and environmental conditions it is time to determine the most effective means of designing, fabricating, and packaging the optical components. One of the most effective ways of ensuring the lowest cost product with the best reliability is to reduce piece part count. On the LAMPS boresight module this was of particular interest because of the stringent boresight retention requirement over temperature and flight. Decisions are made in a meeting type format where the lead mechanical engineer presents the optical layout and his proposed optical and mechanical component breakout scheme. Fabrication producibility engineers from the diamond point machining operation and the conventional machine shop then review and discuss options as well as alternative approaches which will produce the most accurate components with the least amount of dollars. At this point, the designs and concepts are very crude with little detail. The lead ME then goes off to evaluate these ideas and with the help of the opto-mechanical engineer as well as experts in the area of structural and thermal finite element modeling. During this stage of the design process the lead ME, structural experts, and fab producibility engineers can review and update the ProEngineer CAD database simultaneously to reduce design cycle time. Performance budgets are allocated for fabrication, assembly, alignment, and environmental affects and tradeoff decisions are determined largely upon the process sigma levels from the various fabrication processes. Gradually over a series of many iterations, the actual form of the components begin to evolve to a point where a more detailed producibility analysis can be performed by the various fabrication shops. At this point, final dimensional tolerances are defined and component drawings are completed.

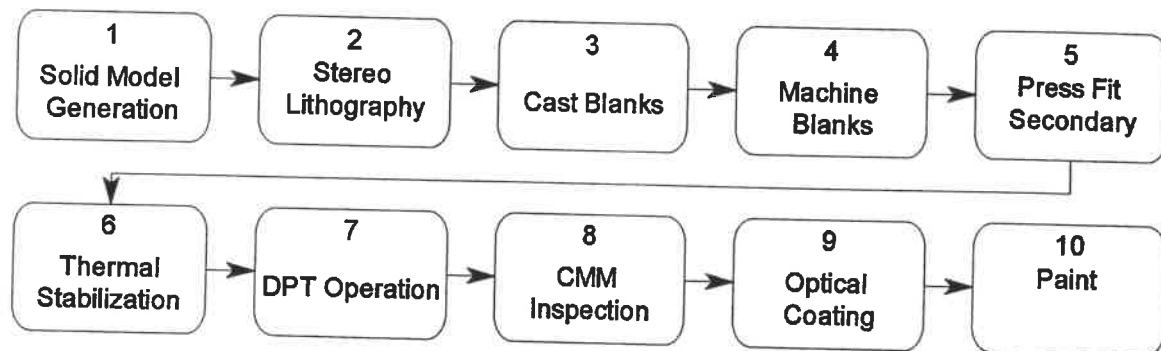
Example No. 2: Material Selection

A critical decision which is made very early before any formal drawings are produced is; What is the least expensive fabrication process which meets all performance criteria? The first step is to answer if Aluminum meets structural and thermal requirements. If yes, then is a hogout cheaper then casting over the projected life of the contract? If yes, then the decision is nearly complete since wrought aluminum is compatible with DPT. If casting is the preferred choice of the blank then more analysis is needed to determine alternative tricks to make cast substrates compatible with DPT. Although cast A201 has been used by TI on a non-imaging production component, the surface finish achieved is less than desirable in applications where scatter is a concern. One common solution is to plate the cast substrate with Electroless Nickel and another is to use a pressed-in wrought aluminum substrate for the mirror surface. The latter approach was used in this secondary housing because of the small size of the secondary mirror. One word of caution when using El Ni plating is that CTE mismatch between Aluminum and El Ni can cause bi-metallic bending of the mirror surface over temperature. One big advantage of El Ni plating is an

improved DPT surface finish as well as the ability to post-polish for use in low scatter applications. This material selection example is just one example of the hundreds of critical decisions which are made early in the conceptual design stage and can have a significant impact on the final performance and cost of the optical system. No one engineer has all of the information needed to make decisions which ultimately affect many areas of manufacturing. This is why, as previously mentioned, the most successful programs in the areas of cost performance and delivery require a tremendous amount of concurrent engineering interaction among the various responsible engineering disciplines.

Fabrication Techniques

Flow Chart 3: Component Flow Diagram (Boresight Module Secondary Housing)



Stereo Lithography (SLA) is a key component in reducing the overall fabrication cycle time. SLA is a rapid proto-typing process used to create casting mold tools. An SLA mold is created directly from the ProEngineer 3D solid model database and is transferred directly to the SLA machine. The SLA process uses a laser beam which cures out a 3D plot of the part in a vat of plastic material. The completed plastic part can then be used as a casting mold tool and the entire casting process can be completed in 2-3 weeks rather than 3-4 months. Stereo Lithography is also used quite extensively on non-cast parts to evaluate component designs for form, fit, and function prior to fabrication.

Conclusions

When the steps of the design and fabrication flow are completed in a concurrent engineering environment then one can expect few surprises during final assembly and test. A system with little engineering concurrency can expect to experience many forms of problems such as component assembly problems, sub-par MTF performance, MTF loss over temperature, energy loss due to excessive surface scatter, and a multitude of combinations of problems which can become quite costly to pinpoint as well as correct.

The Deformation and Registration of a Foil Membrane in an Interchangeable Assembly Process

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Abstract

The subject deals with certain assembly facets of an advanced configuration of the FTM (Flat Tension Mask) color monitor cathode ray tube. The specific configuration incorporates an interchangeable shadow mask process involving specialized techniques of proximity photolithographic screening.

A background is given of the color selective parallax barrier CRT with an emphasis on the accommodation of component and production process irregularities. A brief history of the introduction of the FTM configuration and the evolved interchangeable methodology is discussed.

Items included in the lecture are: 1) The derivation of an optimum geometry for kinematic registry features; 2) Specialized mechanical functions in production lighthouses; 3) Controlled deformation of a foil shadow mask with FEA output examples; 4) Implementation of vision systems in the interchangeable process; and 5) Electronic, optical, and mechanical calibration of the assembly machinery.

DIMENSIONAL VARIABILITY OF STEEL CASTINGS

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Steel foundries in the United States are working to reduce the geometric variability of castings. In 1977, the Steel Founders Society of America (SFSA) completed a comprehensive study of cast feature variability. This study resulted in the creation of empirical models that relate casting design parameters and process parameters to the dimensional variability of cast features. It also resulted in the establishment of "T Grades," currently the only domestic dimensional tolerance guidelines for steel castings.

Since the completion of this study, steel casting processes have undergone nearly two decades of improvements. To gauge the impact of these improvements, the Pennsylvania State University and the Steel Founders Society of America (SFSA) are currently conducting a new dimensional variability study.

Data are being collected from castings produced by representative steel foundries. A wide range of feature geometries and process variables are being analyzed. At this stage, dimensional variability is defined as the estimated standard deviation of a two point measurement. To date, 311 features have been studied on castings weighing between 1 kg (2 pounds) and 1140 kg (2500 pounds). The lengths of the features have ranged from 12 mm (0.5 inches) to 870 mm (34 inches). Thirty measurements were taken from each feature.

This paper presents the results obtained thus far for carbon and low-alloy steel castings produced in green sand, no-bake, and shell molds. These results are compared to the 'T' grades established in 1977. Ninety percent of the features produced by green sand molding had variability less than that recommended by the appropriate T grade, SFSA T5. Similarly, eight-eight percent and sixty-six percent of the features made in shell and no-bake molds respectively had less variability than recommended by the SFSA T3 grade. Comparisons with ISO dimensional standards (ISO 8062) have revealed similar

results.

The data obtained from each foundry has been used to develop empirical models that relate design parameters and process parameters to expected dimensional variability. These models have been provided to the contributing foundries. Armed with these models, the foundries will be able to develop better dimensional control strategies. Eventually models will be developed from the combined data set. In turn these models will be used to establish new tolerance guidelines.

In addition to the analysis of variability, the impact of shrinkage allowances is also being studied. Currently mean pattern dimensions are being compared to mean feature dimensions in order to ascertain the amount of shrinkage. Results thus far indicate that the mean shrinkage agrees with commonly used shrinkage allowances. However a wide range of allowances are currently being used by the industry. Consequently this variability maybe a significant contributor to total geometric variability. Further analysis of industrial data in addition to laboratory trials will be used to develop more robust shrinkage allowances based on molding type and casting geometry.

Flatness, Parallelism and Other Novel Uses of Grazing-Incidence Interferometry in Precision Engineering

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Introduction

The fuel injector of a diesel engine represents one of the most technically challenging articles of manufacture. Due to increasing emission regulations and the demand for improved fuel efficiency, the acceptable size and form tolerances for injector components continuously become tighter. At the same time, the rate of manufacture must be maintained at a level high enough to meet cost targets. It is for these reasons that the manufacturing floor for diesel engine fuel injectors contains state-of-the-art machining and measuring equipment.

Injector Component Form Requirements

Figure 1 illustrates the design of a typical diesel fuel injector of the "unit" design. Unit injectors are so called because they unitize a plunger pump (which is directly driven from the engine camshaft) and injector assembly which provides the mechanism for pressure control, timing, and duration of injection. The action of the plunger causes pressures in excess of 20,000 lb/in² to be produced internally.

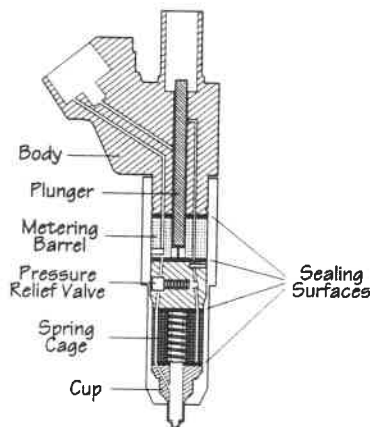


Figure 1 - Unit Fuel Injector

Flat metal-to-metal sealing surfaces, used to retain the pressure, are held against each other under force supplied by the assembly. The form tolerance of the sealing surfaces is often less than 0.001 mm for flatness and parallelism. The leakage path is in the direction of the pressure gradient, which for such an assembly is generally radial. The sealing function is therefore complicated by the radial distribution of the form errors and is therefore an area-weighted effect.

The plunger and its associated nozzle or barrel must also retain the pressurized fuel. The fit of these sliding cylindrical surfaces have form and size tolerances less than 0.001 mm, often exceeding the specifications of XXX class ring and plug gauges. Again the nature of the form tolerance necessitates the analysis of an area; this time in a cylindrical coordinate system.

The components are finished using grinding and honing processes to attain form and size specification. Often the surface roughness requirements are dictated by function, such as oil retention and bearing requirements, which limit the reflectivity to what would not normally qualify for interferometry.

Normal-Incidence Interferometry

The optics community has long used normal-incidence interferometry in the measure of lens surface irregularity. From the simplest instrument such as an optical flat to the most advanced laser interferometer, they all rely on the superposition of a reference wavefront to a wavefront which has been distorted by the surface under test. Figure 2 illustrates a simple

normal-incidence interferometer. Note how the test beam strikes the surface under test at 90 degrees and is reflected back on itself. When the test and reference wavefronts are recombined, the familiar interference pattern is produced.

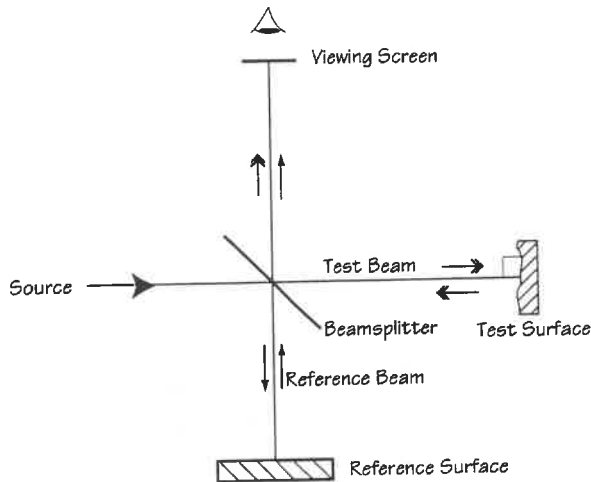


Figure 2 - Normal Incidence Interferometer

Figure 3 shows an interference pattern, each fringe (dark band) represents a line of constant elevation. The distance between fringes, the interferometer "Sensitivity", is

$Sensitivity = \lambda/2$; where λ is the wavelength of the source.

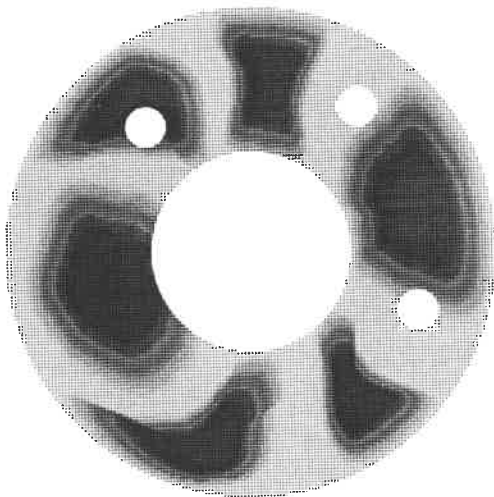


Figure 3 - Interference Fringe Pattern

The HeNe laser is a popular light source for interferometry with a wavelength of $0.6328\mu\text{m}$ and as a physical standard is inherently traceable with a fringe sensitivity of $0.3164\mu\text{m/fringe}$. With modern phase measurement interferometry techniques, a fringe can easily be interpolated to one part in a thousand or less.

As interferometry is a non-contact, massively parallel collection of information it is inherently quick; 250,000 data points are taken, calculated, and displayed in less than 30 seconds with contemporary instruments.

Grazing Incidence Interferometry

Industrial uses of normal-incidence interferometry are somewhat limited because of the need for highly reflective surfaces, and in dynamic range due to fringe pattern crowding. Both of these limitations are greatly minimized in a grazing-incidence interferometer, a schematic of which is shown in Figure 4. The fringe sensitivity for this situation is

$Sensitivity = \lambda / (2 \cos \theta)$; where θ is the incidence angle.

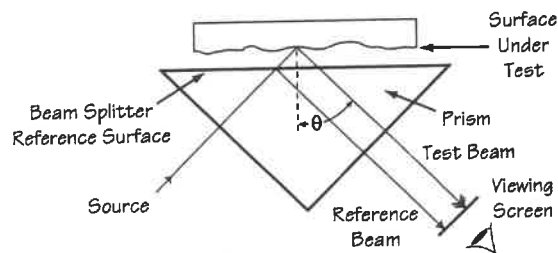


Figure 4 - Grazing Incidence Interferometer

Using the same HeNe laser source and operating at an incidence angle of 85 degrees gives a sensitivity of over $3.6\mu\text{m/fringe}$, which is over an order of magnitude increase in dynamic range. As most form tolerances of industrial components such as diesel injectors are a factor of ten less than that of precision optics, the loss of corresponding precision is not currently a limitation.

Equally beneficial is the dramatic improvement in Rayleigh scattering, and therefore surface reflectivity, which increases as the fourth power of the wavelength ratio. For the above situation, this is over 15000 times improvement. This principle physics of can be easily demonstrated by viewing a normally diffuse surface at grazing incidence as in Figure 5. At a sufficiently large incidence angle the surface will become specular.

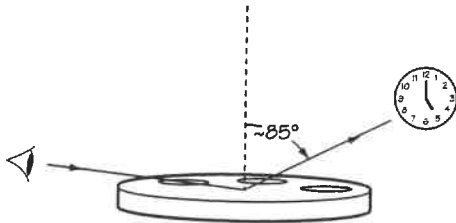


Figure 5 - Observing Specular Reflection at Grazing Incidence

By this method, flatness measurements are easily taken on the sealing surfaces of the injector components. By referencing opposing flat surfaces and calibrating using reversal methods, the parallelism of the component is also calculated. Representative plots are shown in Figure 6. Further profile, radius of curvature, distribution, and other calculations may then be performed and used for machine control.

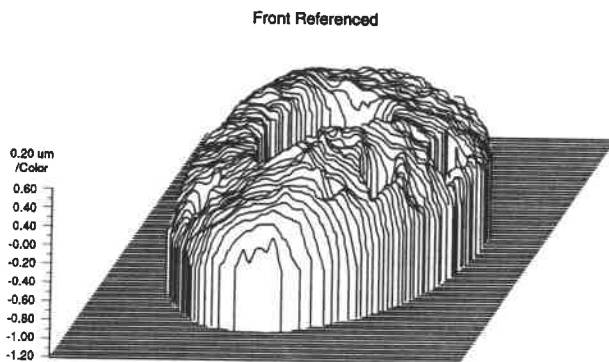


Figure 6 - Flatness Interferometry Measurement Results

Novel Cylindrical Interferometry

While grazing-incidence interferometry has its industrial uses, it is limited to components which are basically flat or with very minimal departure from flat. Most critical components of industrial manufacture are of circular section; fuel injection components are no exception.

To this end Tropel Corporation and Cummins Engine Company are collaborating on the development of interferometers for use in cylindrical coordinate systems. Figure 7 conceptualizes how a grazing-incidence approach might be extended to rotationally symmetric components - if it were possible to arrange an infinite number of infinitely thin prisms about the surface under test.

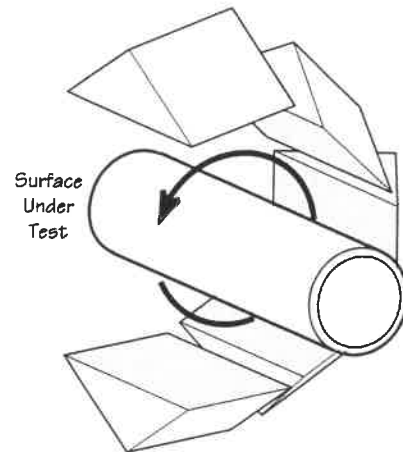


Figure 7 - Grazing Incidence Interferometry on O.D. Cylindrical Surface

Recently it has become possible to produce wavefronts of complex shapes using diffractive optical elements which have encoded into them a digital representation of the desired geometry. In the case of a cylindrical coordinate system the wavefront is axiconic, and is impossible to produce using conventional optics. Figure 8 shows this in schematic form. The test and reference wavefronts used in grazing-incidence are analogous to those referred to

earlier. The fringe patterns may be analyzed, this time with respect to a cylindrical frame of reference, as shown in Figure 9. The measurement of bulk cylindricity may then be reduced to roundness, straightness, and taper components.

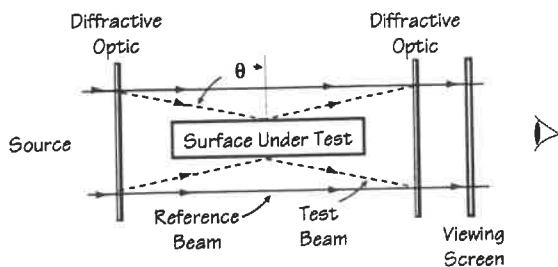


Figure 8 - Diffractive Optic O.D. Interferometer

Summary

By using the grazing-incidence approach to interferometry, precision components such as in Cummins' unit fuel injectors may be measured for flatness and parallelism in non-contact and rapid enough fashion to meet production needs.

Extensions of the grazing incidence approach using newly available diffractive optical elements facilitate the use of interferometry into cylindrical coordinate systems for use on precision bores, shafts, and potentially a wide assortment of other geometries in the future.

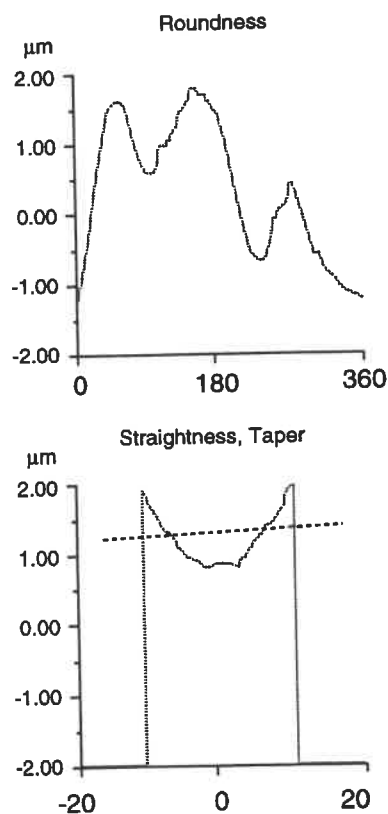
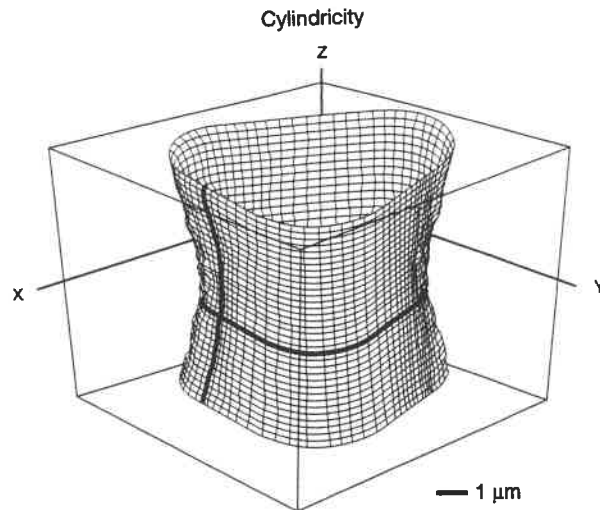


Figure 9 - O.D. Cylindrical Interferometer Measurement Results

Fabrication of Fiber Bundle Arrays for Free-space Photonic Switching Systems

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Abstract

A technique is described for assembling fiber bundle arrays as needed in optical computing and photonic switching systems. Two 4x4 arrays with single-mode and multimode optical fibers were manufactured. Fiber ends were located to within 3 μm of their ideal position and to a pointing precision of 30 arcmin. A third 4x8 array was manufactured with single-mode fibers, and fiber ends were located to within 1.5 μm of their ideal position.

Aligning and Low Temperature Bonding of Multiple Integrated Circuits

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Abstract

This paper describes the process of wafer and chip aligned bonding followed by a low temperature anneal treatment that results in strongly bonded multiple chip and wafer integrated circuit structures that have electrical connections between the chips. The alignment process and initial room temperature bond is created in a modified infrared alignment system that holds two chips or wafers that have received a surface treatment prior to alignment that allows an initial room temperature bond to be produced upon contact. The wafers or chips are critically aligned with infrared illumination while they are held in close proximity in the alignment fixture. When critical alignment is achieved the wafers or chips are brought into contact and the initial bond is achieved. The bonded substrates are then removed from the alignment fixture and annealed with a suitable time and temperature to produce the desired strong bond. Various surface treatments have been found to produce strong low temperature bonds. The most successful treatments found to date include NH_3 and O_2 PECVD plasma and HF wet chemical processes.

Direct silicon wafer bonding has been a topic that has been studied since Shimbo et al. described this process in 1986 [1]. In 1991 Bower et al. described the process of aligned wafer bonding [2, 3]. The aligned wafer bonding technique was then used to produce integrated sensor and integrated circuit structures [4, 5, 6, 7]. In 1993 the process of low temperature bonding (anneal temperatures of 100 to 400° C) was described [8, 9, 10]. Initially, this was based on a nitrogen based chemistry, and later oxygen based surface treatment was described that produced a strong bond after a low temperature anneal treatment [11].

Completed commercial integrated circuits with planarized surfaces have been low temperature aligned bonded. Currently, research is focused on bonding multiple chips including memory to microprocessor and three dimensional memories.

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DIESEL INJECTOR PRECISION ENGINEERING

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Precision engineering for Diesel engine injectors for an engineering and manufacturing company such as Cummins is accomplished via three areas of activity:

1. Functional design and development,
2. Capable process development, and
3. Low uncertainty process control development.

1. By functional design and development, what is meant is the processes of developing a specification by finding a measurable of the component feature which has a deterministic correlation with the acceptable and non-acceptable performance of that component feature. Usually a sizable quantity of product must be measured in the prototype development process in order to establish this correlation. Once this correlation is established then a functional tolerance window can be specified.

2. By capable process development, what is meant is the development of processes used to fabricate the components that are capable ($C_{pk} \geq 1.33$) to the functional specification. This may involve the use of adaptive control or process metrology to improve the C_p or natural width of the process relative to the functional tolerance window. Since process capability (C_{pk}) contains targeting, then a method of holding the process targeted must be developed along with the C_p of the process.

3. By low uncertainty process control, what is meant is the development or acquisition and implementation of low total uncertainty dimensional or performance gaging to assessment dimension or performance of component features relative to the functional tolerance window. The measurement technique should not only have low repeatability (high precision), but also have small targeting or bias errors.

The relative importance of repeatability and bias will be discussed relative to the functional tolerance window and the quality of the component production. It will be shown that if these situations are met then a zero defect production of the component feature will be realized. The details of how this is accomplished for several ultra-precision injector components will be presented. Not only will the discussion cover machining processes, but will also deal with precision and measurement in coating processes and assembly processes. Cleanliness issues for assembly and performance will also be covered.

Evolution in the Requirements for Surface and Form Measurement

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Abstract:

Tightening dimensional tolerances have squeezed the requirements for surface and form precision. Very few guidelines exist in the United States to help the designer or manufacturer in how to specify or measure these characteristics. Some work has existed in DIN, ISO and East Germany which has recognized this phenomenon.

Part Function requirements drive these tighter tolerances. Form and surface quality are clear contributors to part functionality. Parameter proliferation has occurred because traditional measurement parameters only address process stability instead of part suitability for its intended function. Current trends are moving to define parameters which correlate to function. This work has addressed areas of filtering, frequency of measurement sampling, asperity suppression, area analysis, etc.

Through more active participation in ISO, US industries have had more access and influence on the work done (mainly) in Europe. EC Standardization has led to work in surface and form measurement, particularly in the unification of diverse standardization philosophies. This has established a more open forum for airing many different national approaches, making for interesting times.

At the top end of the tight-tolerance pile, EC standards are pushing to leave no loose ends. This is leading to the "standard" defining the ultimate piece of arbitrator equipment.

Cylindricity measurement is an excellent example of this process. It is an integrated parameter, which is primarily functional. Because of the available computerized data reduction, it allows analytical work to come out of the functional check.

The Joint Harmonization Group is working to bridge the divergence which exists in the metrology community. TC-57 (Surface finish/Form), TC-3 (Technical Drawings), and TC-10 (CMM) committees are looking for a common ground on which to establish agreement between discrete-point and traditional methods of cylindricity assessment.

Current Trends in the Packaging of Photonic Devices

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Abstract

Optoelectronic and photonic devices hold great promise for high data-rate communication and computing. Their wide implementation was limited first by the device technologies and now suffers due to the need for high-precision packaging that is mass-produced. The use of photons as a medium of communication and control implies a unique set of packaging constraints that are highly driven by the need for micron and even sub-micron alignments between photonic devices and their transmission media. Current trends in optoelectronic device packaging are reviewed and future directions are identified both for free-space (3-dimensional) and guided-wave (2-dimensional) photonics. Emphasis will be placed on the special needs generated by increasing levels of device integration.

MICRON-SIZE MILLING TOOLS: FABRICATION AND USE

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Extension of conventional machining techniques into the realm of micron scale fabrication is one objective of the Institute for Micromanufacturing. The scope of the project is broader than obtaining small, micron sized features with surface roughness in the sub-micron range such as can be produced by diamond point machining. We are searching for techniques to make millimeter (or larger) sized objects which contain features that are measured in microns and which have micron or sub-micron tolerances.

Mass production of mechanical or electromechanical devices with these dimensional requirements is expected to be done by x-ray lithography in which an absorber mask is used in a proximity printing process to imprint the high aspect ratio pattern into a photo-active material such as polymethyl methacrylate (PMMA). The depth of the x-ray exposure and the subsequent feature height is being pushed to the millimeter scale. After development, the PMMA with imprinted pattern is then used as a master to make durable metal molds by an electroforming process (this is the process known by the German acronym LIGA). Mass replication of parts is done by molding and electroforming. The complete process outlined above is a very expensive and time-consuming one, due in part to the need for an x-ray absorber mask, and in part to the need for an intense source of x-rays, such as a synchrotron. There is often no guarantee that the devices or system of devices produced by this technique will be successful. Rapid alternative methods to produce the replication pattern independently of the x-ray technique are therefore desirable from an economic standpoint.

High precision machining with micro-tools is one possible alternative to the x-ray lithographic technique for the production of the mold. Micro-machining a mold can be useful as an inexpensive and rapid method to make prototypes of the device to be mass produced. Micromachining of molds could also be a means to production, if the prototype meets the design criteria. The driving force to extend conventional machining techniques to the micron tolerance level is considerable: material removal by milling to make such shapes is feasible if tools were available. Milling tools with diameters (of the order of $20\mu\text{m}$) required for this application are not available, and neither is there a body of experience to draw from.

The purpose of this work is to fabricate milling tools and establish machining techniques that will remove material from PMMA with micrometer dimensional stability over millimeter distances. The work divides naturally into two parts: Fabrication of the milling tool by focused ion beam (FIB) techniques, and application of the tool in the material removal of PMMA.

Focused ion beam machining of milling tools

Cutting surfaces and features were created by focused ion beam machining, which is a vacuum process utilizing a 20keV beam of Ga ions to sputter material. The ion beam used in this work has a nominal $0.5\mu\text{m}$ diameter (full-width at half maximum, for a Gaussian

distribution) and is deflected by a digitally driven vector scan with sub-micron resolution. The FIB technique has been used to make scanning probe microscope styli from polycrystalline metals and from single crystal silicon, with probe diameters of the order of $0.2\mu\text{m}$ which taper to points with radii of curvature at the 10-50 nm level [1-4]. The FIB method has since been expanded by addition of rotational substrate motion so that a full 360 deg of the work piece is accessible to the ion beam [5,6]. Three dimensional microstructures are created with virtually no restrictions on geometry, with dimensions ranging from $150\mu\text{m}$ to $1\mu\text{m}$, and sub-micron resolution. Grain size has been shown to limit the dimensional resolution in some polycrystalline materials [4-6].

Tool blanks were 1.0mm (0.040") dia high speed tool steel which were tapered to a cylindrical segment 1.5mm long and 0.025mm (0.0010") dia by diamond grinding. Tool blanks were obtained in this geometry from a commercial supplier. The 0.025mm dia cylindrical segment was cut off by ion milling to give the desired working surface length. The working length was typically 40 to 60 μm after the taper ended in the cylindrical segment. First attempts to make milling tools on this scale used a direct analog of a macroscopic tool as a model for the geometry. These were tools containing four flutes 90 deg apart or two flutes 180 deg apart, with a $25\mu\text{m}$ length of the cutting flute, and a depth of $2\mu\text{m}$. Milling with tools that were scaled down from macroscopic geometry was unsuccessful, and scanning electron microscopic (SEM) examination of the tool surfaces before and after milling showed two pertinent features: 1. The ion milling technique needed to produce the cutting edge in the tool surface accentuated the grain structure of the tool steel, giving an irregular cutting edge relative to the scale required. 2. Material adhered to the tool, most likely as a result of the geometry of the cutting surfaces and insufficient relief for chip removal.

A simpler tool geometry was evident from these first attempts. A pair of flat surfaces were ion milled along the axis of the cylindrical segment in such a way that two extremely sharp cutting edges were diametrically opposed. A specific ion milling sequence or procedure was found so that there was no effect from grains on the definition of the cutting edges. The normal Gaussian distribution of the ion beam intensity also has no effect on the radius of curvature of the two cutting edges with the correct ion milling sequence. The intensity distribution of any focused ion beam limits the sharpness of corners at the boundaries of the cut, under most circumstances. The flat geometry must also be optimal for chip removal since comparatively little material was found to adhere to these tool surfaces.

Micromilling of PMMA

Milling of PMMA by the micro tools was performed on a modified National Jet 7M manual microdrilling machine. The PMMA work piece was held in a fixture which was moved by a stepper-driven stage at 35 μm per second feed rate. The milling tool was rotated in double vee-blocks by a servo motor, a collet pulley, and an endless nylon belt at a rotational speed which was varied between 10,000 to 16,000 rpm. This speed range was selected to help ensure the tool would not be broken due to excessive forces from too thick a chip and 16,000 rpm was the upper limit of the then available machine. The tool spindle was fed into the work piece along the spindle axis by another stepper-driven linkage. The axial engagement of the tool into the work piece was 1.14 μm and this was repeated for up to 20 passes for a total trench depth of 22.8 μm . Each trench had a total length of 2 mm. Approximately one minute

was required to complete a 2mm long pass. The milling was performed both with and without a lubricant to determine the effect on the trench width, the slope of the side walls and the bottom roughness. The entire milling process was under computer control and was viewed through a video microscope.

The trenches were deburred after milling by a 2 minute exposure to a 1:1 solution of acetone and isopropanol. Each trench was measured with a WYKO RST interferometric microscope at 40X, giving a lateral resolution of approximately $1\mu\text{m}$. The trench width was taken at the zero mean location of the cross section rather than at the top or bottom. The sidewall slope was measured along the straight portion of the wall from the top of the trench to near the bottom. The transition from the sidewall to the bottom was not a sharp break but rather had a radius of about $1\mu\text{m}$. The width, sidewall slopes, and cross sectional bottom roughness were measured at 50 points along each trench. Data for four rotation speeds and two different tools are summarized in the table below.

PMMA Trench Dimensions and Roughness

Cutting Conditions Are Dry, Depth/pass = 1.14 microns, Feed = 35 microns/sec

Tool #, Dia	Speed (rpm)	Width (microns)	Slope Left (deg)	Slope Right (deg)	Roughness (nm)
6 (22.9 μm)	10000	23.86	77.27	78.23	158.19
6 (22.9 μm)	12000	23.59	80.17	82.78	164.49
6 (22.9 μm)	14000	23.04	82.38	82.62	152.93
6 (22.9 μm)	16000	23.38	83.40	85.07	107.51

Cutting Conditions Are Using Oil, Depth/pass = 1.14 microns, Feed = 35 microns/sec

Tool #, Dia	Speed (rpm)	Width (microns)	Slope Left (deg)	Slope Right (deg)	Roughness (nm)
5*	10000	21.84	81.66	81.36	292.62
5*	12000	20.75	85.44	86.08	266.61
6 (22.9 μm)	14000	23.80	85.70	85.84	129.74
6 (22.9 μm)	16000	25.53	85.98	85.96	90.57

* Diameter not available, tool had been used to mill aluminum prior to PMMA

The above data show that the trench width accurately reflects the diameter of the milling tool, with the only significant variation occurring for tool #6 with oil at 16000 rpm.

Surface roughness obviously decreases significantly with the highest rotation speed, regardless of the presence or absence of lubricant. The trench width variation was $-0, +1\mu\text{m}$ over the 2mm length.

These data support the possibility of being able to create macroscopic (millimeter) sized features with micron tolerances by scaling down conventional machining techniques. The fundamental finding is that the tool geometry departs from the scaled down analog of its macroscopic counterpart. Extensions of these studies with an interferometrically controlled micro-machining device with dimensional resolution of 1.25 nm (National Jet/Dover) will begin in the near future, and additional variables such as the linearity of cuts, etc will be measured.

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A SIMILITUDE ANALYSIS FOR MINIATURE MACHINING

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ABSTRACT

The processes for machining miniature parts can be related to similar processes for machining conventional size parts. The analytical approach used in similitude--the study of similarity between systems (often used for designing models)--provides an insight into important aspects of miniature machine tools. Machines to make very small parts are not necessarily small machines. For example, it is more important to scale the straightness-of-motion than to scale the overall size of the machine when designing for miniature machining. A similitude analysis aids in the understanding of important parameters in designing processes for miniature machining.

Introduction

Physical models are designed by rules and approaches studied in a field called similitude. If a model and prototype meet the requirements of similarity, then measurements made in the model system can be used to predict results in the prototype. Usually the model is a system that is easier to build than the prototype; and therefore, it makes sense to do experiments on a model and calculate the corresponding results in the prototype system without incurring the expense of actually building the prototype. This paper proposes that the same philosophy is valuable for designing a miniature machining process. In this case think of the "model" as a conventional size machining process, which we have easy access to and that we can experimentally study, and then think of the "prototype" as a system that we have not yet built that will be used for machining very small parts. Usually we think of the prototype as the larger system, such as the case when using wind tunnel models to study aircraft, but that is not a requirement, and here we are thinking of the prototype as a machining system for very small parts. For example, if we want to design a machining system for making a 100-micrometer diameter part (in this paper called the prototype), then we can do studies on a more conventional size part, say 10-mm diameter (here called the model) which is 100 times larger. If we design the systems completely similar, we could do things like measure the cutting force in the model system and calculate the cutting forces to expect in the prototype (if we have the correct model-to-prototype relationship for forces).

An approach normally used in similitude is to require complete geometric similarity, or in practice this means that we scale all length dimensions of the prototype by the same factor. If we use this approach for designing a machining process for making miniature parts, we could argue that we should use a smaller machine tool, or one "scaled down", to make very small parts. For example, if we machined a 10 mm diameter part on a lathe that is about 500 mm by 1000 mm (like a standard tool room lathe), and we wanted to now machine a part that is only 0.1 mm diameter (100 times smaller than our first part), we should be able to also scale all dimensions of the machine by a factor of 0.01 (making our miniature machine a 5 mm by 10 mm lathe). If we did the design of the new miniature machine correctly, the part produced should be exactly "similar" to the original part. In other words, if we photographed the miniature part at 100X in a scanning electron microscope (SEM) it should "look" identical to the conventional part photographed at 1X. Often, very small parts enlarged in an SEM photo do not appear to be large parts reduced--the miniature parts sometimes look relatively rougher, meaning that we probably do not have completely similar systems for making small parts.

Geometrical Similarity

Similarity is an extension of geometrical similarity¹. In a rather simple example, from basic Euclidean geometry, two triangles are similar if they have two angles respectively equal. As a

result of being similar the sides of the triangles are respectively proportional. For example, if side "A" of one triangle is related to side "a" of the other similar triangle by a constant, k , (sometimes called a scale factor), where $k = A/a$, then the relationship of the other sides can be determined with the same scale factor, $B = k b$ and $C = k c$. In more general terms, two systems are geometrically similar if all pertinent angles are equal in the two systems, and all corresponding variables measured with length units in the two systems are proportional. Geometrical similarity is one of the requirements of complete similarity; however, for complete similarity all variables in the two systems, such as velocity, force, stress, etc., have to also be proportional--but not necessarily related with the same scale factor as the length dimensions. A similitude analysis determines the relationship of all pertinent variables of a model to the prototype system.

In examining a miniature machining problem from the standpoint of similitude, we can start with a miniature part that we would like to make. For example, Figure 1 shows a small plug, with the dimensions labeled. We call this part the prototype. We can easily make a more conventional size part, say 10-mm diameter, on a tool room lathe. We can design this conventional size part, here called the model, by using a scale factor, k , relating corresponding dimensions. Using the diameter as the reference length, $k = \text{diam. prototype} / \text{diam. model} = 0.01$, then we can design the model by, $x \text{ prototype} = k \text{ times } x \text{ model}$, where x is any corresponding length in model and prototype. The resulting model is shown in Figure 2.

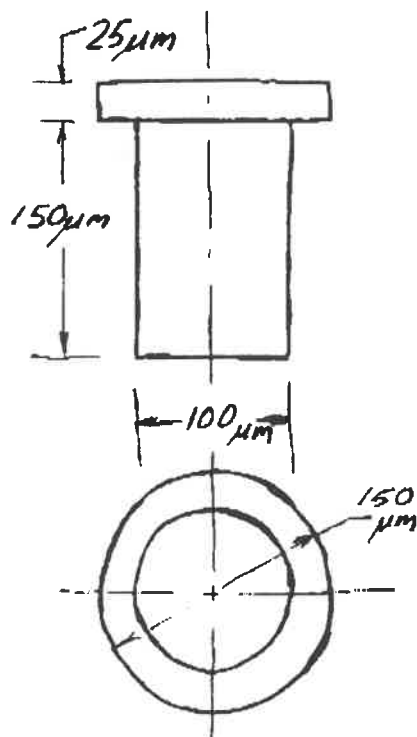


Fig. 1. Miniature Part: The Prototype

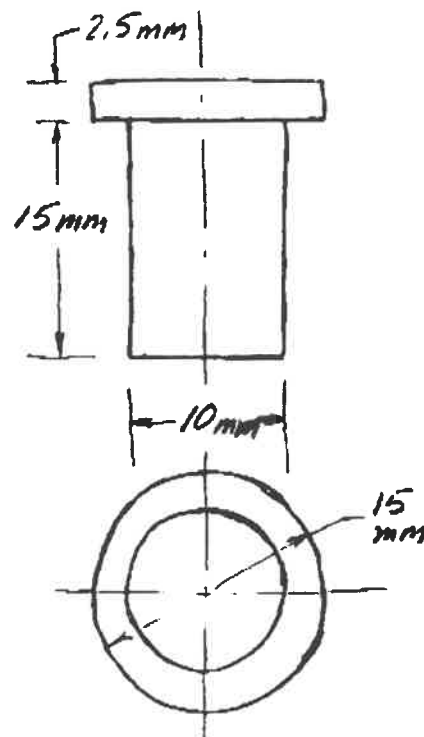


Fig. 2. Conventional Part: The Model

All dimensions and length variables need to be scaled with the factor k . Some of these variables needed for geometric similarity are summarized in Table I. The model values, shown in the second column of the table, are the specified dimensions of the model part shown in Figure 2, plus values of parameters measured on the conventional machining system. (In the case presented in this paper, some parameters are my estimates that would be measured if we used a standard tool room lathe. In actual practice we could measure all of these parameters. I think the magnitude of the numbers presented here are reasonable.) The third column contains the parameters that describe the prototype part plus the length variables that would have to be specified when designing the new miniature machine to be similar to our conventional machine described by variables in the second column of Table I.

TABLE I Comparison of Model and Prototype Geometry

Parameter (all measured in length units)	Size in Model	Size in Prototype
PART DESCRIPTION		
diameter	10 mm	100 μm
cap diameter	15 mm	150 μm
length	15 mm	150 μm
cap length	2.5 mm	25 μm
PROCESS PARAMETERS		
tool feed, length/rev	25 μm	0.25 μm
depth of cut	50 μm	0.5 μm
tool tip radius	250 μm	2.5 μm
sharpness rad of tool	5 μm	0.05 μm = 50 nm
spindle error motion	2 μm	20 nm
slide straightness (for length of part)	1 μm	10 nm

If we now make the model by machining it on a tool room lathe, we can measure length variables in our resulting model system and calculate the corresponding variables that will result when the prototype part is made on our new miniature lathe--a lathe built to be completely similar to our tool room lathe. For example, if we measure a surface finish on our model to be, $R_a = 1$ micrometer, then we calculate a resulting surface finish of 10 nanometer R_a for our prototype part (R_a prototype = k times R_a model). Other dependent geometric variables might be straightness, roundness, corner radii, etc., that are handled in the same way as surface finish.

This analysis of geometric similarity between the two systems illustrates why it is very difficult at times to make small parts. Achieving the approximate required dimensions of the prototype part may not be difficult; however, achieving a spindle with a total error motion of 20 nm will be difficult. Spindles with this level of error motions are often fairly large and may not look like a miniature machine component; however, from this consideration overall size is not important, only those things that actually affect the part.

Stress and Force

In addition to geometrical similarity other variables of the system have to be considered. If we consider the case where we make the prototype and model part from the same material, then material properties will be the same in both systems; for example, the flow stress of the material, σ_o , is an important parameter that will be the same in both the prototype and model. If we define the flow stress as the stress caused by the cutting force as the chip is formed in the machining process, then

$$\sigma_o = \frac{f_c}{t_o w}$$

where f_c = cutting force, t_o = depth-of-cut, w = width of cut. Because the material is the same in the prototype and model

$$[\sigma_o]_{\text{model}} = [\sigma_o]_{\text{prototype}}, \text{ or}$$

$$\left[\frac{f_c}{l_o W} \right]_{model} = \left[\frac{f_c}{l_o W} \right]_{prototype}, \text{ and}$$

$$\frac{f_{c, prototype}}{f_{c, model}} = k^2$$

Where k is the length scale factor.

In our example of machining the part in the geometrical similarity discussion above, $k = .01$; and therefore, the forces in the prototype system will be 0.001 times the forces in the model system. In other words, the forces in our new miniature machine, if we truly maintain similarity, will be very small. If we depend on the "feel" of the operator when using the standard tool room lathe in making this part, it certainly will not be possible to feel the cutting force in our miniature system. It could be an advantage in the miniature system that the forces are scaled by the length scale squared, in that the forces caused by cutting are extremely small; however, the deflections in the machine caused by cutting forces would be scaled by the same length scale, k .

In actual practice it may be difficult to scale the depth-of-cut because of the size effect in machining. Some research shows that the specific energy (the same units as stress) goes up as the depth of cut gets very small (on the order of a micrometer or less)². This means that the force has increased for small depths of cut greater than our similarity analysis predicts. There are indications that this effect is related to the edge sharpness of the cutting tool. The problem with our scale model approach is that it may not be possible to produce a tool with edge sharpness scaled by our factor of 0.01. Therefore we may have to have a distorted model and use depths-of-cut larger than would be dictated by geometrical similarity. In this case the forces would be such that the deflections in the miniature system would be relatively greater and maintaining a scaled tolerance might be impossible.

Conclusions

The similitude approach is helpful in examining various parameters needed to design a miniature machining system. A more complete analysis than the one presented here will consider additional important aspects such as vibrations. Geometrical similarity requires that we consider all length variables that may affect the part, even error motions. Considering the overall size of the machine is not as important as considering parameters such as error motion. It may be easier to achieve the required error motions in large machines; and therefore, with only casual observation, machines for miniature parts may appear to be too large.

¹Skoglund, V.J., *Similitude: Theory and Applications*, International Textbook Co., Scranton, PA, 1967, pg. 15.

²Lucca, D and Sco, Y., "Effect of Tool Edge Geometry on Energy Dissipation in Ultraprecision Machining", *Annals of CIRP* Vol.42/1/1993.

MICRO ADJUSTMENT BY ELASTIC AND PLASTIC MATERIAL DEFORMATION

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Introduction

High precision devices, used in research, development or production often require a very accurate position adjustment of their parts. For this purpose many types of precision displacement transducers are incorporated within these devices. The desired values of minimum adjustment steps can vary from several micrometers down to parts of a nanometer.

Many of these displacement transducers (micro-actuators) are based on material deformation of especially designed parts of the transducer structure. In most cases, the material deformation is strictly elastic. Although, some new adjustment methods have been developed within the electronic industry using plastic permanent material deformation for the very accurate adjustment of parts¹. These devices use a smart combination of elasticity, plasticity and laser induced heat to achieve a permanent stepwise spacial adjustment of parts such as read/write heads of VCRs². The common feature of both types of transducers is in fact the dominant influence of the stiffness ratio between two main parts of these devices.

Transducers based on elastic deformation

In general, it is desirable to use relatively large, easy to control input movements to obtain the intended small and accurate output displacements. Therefore, a large reduction of the input displacement must be realized. Devices, based on elastic deformation of their structure, offer a number of remarkable properties for these purposes. Most of these devices consist of two connected elastic structures (springs) with a high mutual stiffness ratio.

In most cases, these elastic structures can be made from a single piece of material by spark erosion or metal etching. Due to their high structural integrity and strictly limitation to elastic material deformation, these devices possess a very good linearity, high stability, extremely low hysteresis

and a low thermal sensitivity. Often, it is possible to use their intrinsic accuracy of the input/output displacement ratio without the need for a feedback control of the output displacement. The input displacement can be provided by manually controlled micrometer screws or electrically operated actuators, such as piezo elements.

In the category of precision elastic actuators there are a number of commercially available devices. Among them, the excellently designed actuators of AEH Inc.³ are the most beautiful examples of this type of elastic structure. However, it must be recognized that in some cases custom-made actuator designs are inevitable. One of the main reasons for such custom designs in our field of research often is the extremely small space available for the actuator. For example, experimental set-ups for micro positioning of sample holders in electron beam microscopes must deal with the very limited volume available for additional devices.

The aim of this paper is to describe the necessary steps for an optimum design of small actuator structures. To avoid any confusion, only the design of the elastic structure (the displacement transducer) will be considered. Powerful computer tools, such as finite element analysis, can be used to support the design process. However, these tools usually do not provide the designer with design rules when started from scratch. It must be recognized that only a few design parameters can really be chosen freely, as most of them have a strong mutual dependency.

We will be presenting a limited number of design strategies. One of the strategies focuses on minimum outside dimensions of the actuator at a given stiffness of the actuator structure. Simple stress and stiffness equations have been used to determine the actuator parameters. If precise calculations are required, fine tuning of the actuator properties can usually be carried out by finite element analysis using the previously estimated parameter values.

Basic assumptions

In this paper, design strategy will be shown for a simplified common type of the elastic displacement transducer (see figure 1). However, the results presented are valid for a large number of similar devices. All these devices can be characterized as structures with two spring systems which possess a large mutual stiffness ratio.

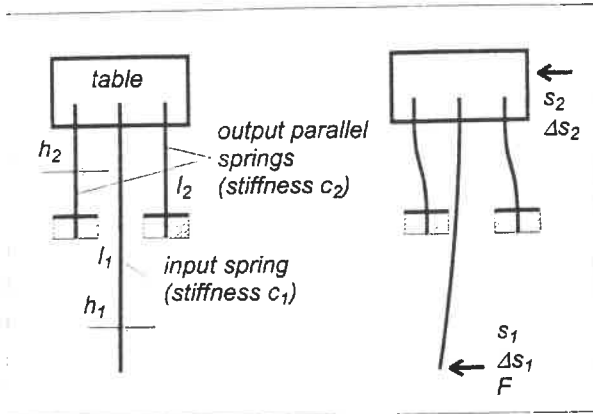


Fig.1. Schematic structure of the displacement transducer with its most important parameters

In general, two parameters of the transducer are very important: the minimum value Δs_2 (resolution) of the output displacement and the range s_2 of this displacement. It is convenient to use relatively large, easy to control input movements. Therefore, the resolution of the input displacement Δs_1 usually is limited to a certain value. If, for example, a micrometer screw serves for the input displacement, the resolution is in the range of a tenth of a micrometer. Very often an extremely low value of the resolution Δs_2 along with a large value for the output range s_2 is required. It must be recognized that these two factors are in fact conflicting. However, to a certain extent, it is possible to combine low Δs_2 with a reasonably large s_2 . For example, a nanometer resolution with a micrometer range can be combined relatively easy.

Another obvious requirement is a high mechanical stiffness c_T of the transducer in the direction of the output displacement. The following calculations will show a strong relationship between the overall transducer dimensions and the mechanical stiffness. Small dimensions lead inevitably to a low stiffness. As the value of the

input force F is often limited, the transducer stiffness cannot be chosen freely also for this reason.

As previously mentioned, often small transducer dimensions are required in the field of micro engineering. Therefore, it is important to be aware of the influence of all transducer parameters on the dimensions of the device. For the described type of transducer the following statement can be used:

$$\frac{\Delta s_2}{s_2} = \frac{\Delta s_1}{s_1}$$

In fact the main task of a displacement transducer is the reduction of displacements. Therefore, a displacement reduction ratio must be defined:

$$R = \frac{s_2}{s_1} = \frac{\Delta s_2}{\Delta s_1}$$

The schematic structure of the transducer from figure 1 uses a cantilever spring as an input spring system and a parallel spring guiding of the transducer table as the output spring structure. In a more schematic way, this type of transducer naturally can be seen as a combination of two serial springs loaded with the same force F . Therefore, it can be written:

$$s_1 = \frac{F}{c_1} + \frac{F}{c_2} \quad \text{and} \quad s_2 = \frac{F}{c_2}$$

The reduction ratio can be written as a function of both stiffnesses:

$$R = \frac{c_1}{c_2 + c_1}$$

For many reasons, high stiffness c_T of the transducer "table" is required:

$$c_T = c_1 + c_2$$

As mentioned previously, the reduction of displacements should be very large or the reduction ratio must have a very low value ($R \ll 1$). Therefore, the transducer stiffness c_T can also be written as:

$$c_T = c_2 = \frac{c_1}{R}$$

The transducer design can be divided in two main parts, the design of the input cantilever spring and the design of the output spring structure.

Design of the input cantilever spring

The spring length l_1 usually has a very strong impact on the overall dimensions of the transducer. Therefore, small transducers can only be realized with small input cantilever springs. Generally, the value of l_1 depends on many parameters, such as

allowable material stress σ_{max} , Young's modulus of elasticity E or the desired system stiffness c_T . One of the most important limitations in the design of a spring is the allowable material stress. It must be recognized that, for the benefit of low transducer hysteresis, usually relatively low stress values may be used. These stress values often are based on the particular experience of the designer; there is no much knowledge about the relationship between stress and hysteresis. For example, the AEH company uses high quality aluminium (6061-T6) combined with the relatively low allowable stress value of 70 MPa.

The cantilever spring must also possess an exact stiffness value, which again is determined by a number of parameters. There is a clear relationship between the driving force F , the input range s_1 and the transducer stiffness c_T :

$$F_1 = c_1 s_1 = R c_T s_1 = c_T s_2$$

Using the simple equations for cantilever spring tip displacement and for maximum spring stress, the following requirement for minimum spring length can be found:

$$l_1 \geq 2.38 \frac{s_1}{\sigma_{1max}} \sqrt[3]{\frac{R c_T}{b_1} E_1^2}$$

The accompanied spring thickness is then:

$$h_1 = \sqrt[3]{\frac{4 R c_T}{b_1 E_1}} \cdot l_1$$

However, in this equation both parameters b_1 and s_1 have a certain relationship with the cantilever spring length. It is obvious that the shorter length l_1 can be obtained with a larger value of the spring width b_1 . It must be recognized that the cantilever spring width should be within some reasonable boundary, for example:

$$b_1 \leq 0.2 \cdot l_1$$

For this type of transducer, it is reasonable to choose the cantilever spring length of not shorter than $10 \cdot s_1$. For the ratios $l_1/s_1 < 10$, the deflection of the cantilever spring is too large (the deflection angle is too large) to guarantee a linear relationship between the actuator input movement and the driving force F . As a consequence, the reduction ratio will differ from the desired constant value. Of course, the ratio $l_1/s_1 > 10$ is reasonable when starting with a straight unloaded cantilever spring. However, a bend shape of the spring unloaded condition usually doubles the possible displacement input range (l_1/s_1 can approach a value of 5).

By using the ratio $l_1/s_1 > 10$, it can be stated that the shortest cantilever spring length l_1 is:

$$l_1 \geq 10 \cdot s_1 = 10 \cdot \frac{s_2}{R}$$

This means that the shortest cantilever spring length can be determined directly from the desired output range of the transducer! However, if this shortest length l_1 is chosen, the overall transducer stiffness will be limited to a certain value:

$$c_T = 148 \frac{s_2}{R^2} \frac{\sigma_{1max}^3}{E_1^2}$$

If this stiffness value is not high enough, the cantilever spring length must inevitably be chosen larger than the minimum value:

$$l_1 \geq 2.86 \sqrt[3]{s_1^3 R} \sqrt[3]{\frac{E_1^2}{\sigma_{1max}^3}} \sqrt[3]{c_T}$$

or in terms of output range s_2 :

$$l_1 = 2.86 \sqrt[3]{\frac{s_2^3}{R^2}} \sqrt[3]{\frac{E_1^2}{\sigma_{1max}^3}} \sqrt[3]{c_T}$$

In general, if s_2 and material are chosen, the length depends only on the required stiffness:

$$l_1 = K_1 \sqrt[3]{c_T}$$

However, there is an upper stiffness limit dictated by the maximum force F_a of the applied input displacement actuator:

$$c_T \leq \frac{F_a}{s_1} = \frac{F_a}{s_2} R$$

Design of the output spring system

In most cases, it is desirable to use two parallel springs for the output spring system. This configuration guarantees an almost linear movement of the transducer table. Using the same spring formulas as in the previous section, the lower limit for the spring length and the spring thickness can be found:

$$l_2 \geq 2.38 \frac{s_2}{\sigma_{2max}} \sqrt[3]{\frac{c_T E_2^2}{b_2}}$$

$$h_2 = \sqrt[3]{\frac{c_T}{2 b_2 E_2}} \cdot l_2$$

In general, the condition for l_2 does not form any serious limitations for the design. Usually the limit is far below a convenient spring length. From the spring energy equations it can be stated:

$$\frac{\text{energy stored in the output spring}}{\text{energy stored in the input spring}} = R$$

For this reason, the ratio of spring material volumes also is equal to R . Therefore, the dimensions of the output springs never could form a serious limitation to the transducer volume.

Finite element analysis

As stated previously, simple stress and stiffness equations have been used to determine the mutual dependencies of the transducer parameters. However, additional finite element calculations of some transducer structures showed that even these simple equations provide surprisingly accurate results for the transducer design.

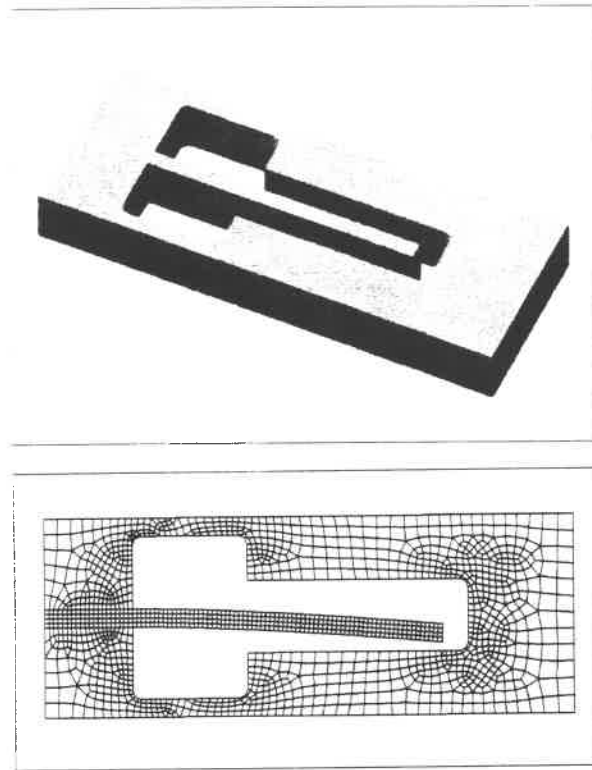


Fig.2. Solid model of a transducer and a finite element analysis of its displacement.

Figure 2 shows the results of FEA for the transducer displacement of one of the structures considered. This flat structure has the following outside dimensions 34*12*4 mm.

Material selection

The previous formulas for the transducer stiffness c_T and the input spring length l_I show also a strong influence of material selection upon both parameters. As an example, in the following table the important material ratio $E_I/\sigma_{I\max}^3$ is given

along with E_I and $\sigma_{I\max}$ for three different materials:

material	E_I [GPa]	$\sigma_{I\max}$ [GPa]	$E_I^2/\sigma_{I\max}^3$
aluminium	70	0.2	60e-5
steel	200	1	4e-5
Ti6Al4V	105	1	1e-5

If the minimum length l_I is considered, the transducer stiffness c_T for a steel structure is 15 times larger and for a titanium alloy structure even 60 times larger than the stiffness of a device made of aluminium. If the stiffness c_T is the main criterion, then, taking all three materials into consideration, the length ratio for l_I is 1 : 0.5 : 0.35. The titanium alloy provides clearly the shortest spring. For practical reasons, two different materials for both spring systems can be considered. For example a steel input spring can be combined with an aluminium transducer structure with integrated output parallel springs. There is a limitation in manufacturing for relatively small integral devices, as the springs can become very thin. Usually the lower thickness limit is in the order of 0.1 mm.

Conclusions:

From this paper the following design rules can be formulated:

- Displacement transducers with a very small output resolution and a large output range will inevitably have large dimensions.
- If small transducers are required, only a limited value of the structural stiffness can be realized. However, a proper material choice will substantially improve the design parameters.
- The calculations presented give reliable results for all important device parameters.

References and remarks

- [1] European patent No. 0 488 658 A2 from Matsushita Electric Industrial Co., Ltd.
- [2] The proposal was made to discuss also this type of transducer in this paper. Unfortunately, just before the deadline of March 3, the collaborating Dutch manufacturer demanded the concealment to this part of our contribution.
- [3] Alson E. Hatheway Inc., 595 East Colorado Blvd., Pasadena, CA 91101

DIAMOND TURNING PRODUCES HIGHER QUALITY AIR BEARINGS

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INTRODUCTION

Two axis diamond turning machines have been commercially available for nearly 25 years. During that period of time they have been used almost exclusively for the production of metal optics, and for the manufacture of molds for cast or formed optics. A few organizations have explored the use of these high precision tools for the manufacture of surfaces which are not optical in function¹, but serve to align components which are essentially optical in nature.

THE PROBLEM

The accuracy which can be built into any mechanism is a function of the accuracy of the machines used to produce the parts of that mechanism. This is as true of air bearings as it is of optical instruments. If a diamond turning machine can produce accurate optical surfaces, why not use it to manufacture the component parts of air bearings? In recent years, we have begun to utilize the accuracy of our diamond turning machines to improve the quality of air bearing spindles used for both machining and metrology applications. As the radial and axial error motions of the conventionally produced air bearing spindles used on our diamond turning machines is on the order of 50 nm, it was reasonable to expect that bearings whose components are produced on these spindles would exhibit even better accuracy.

MATERIAL SELECTION

The primary problem was to choose materials which are machinable with diamond tools and, are mechanically suitable for use in the bearings that we wished to construct. While it is certainly possible to use carbide cutting tools on a diamond turning machine, our feelings at the time were that the lower forces present in diamond turning would contribute to the accuracy of the finished parts. We could also have considered the use of plating to put a diamond machinable surface on an otherwise unmachinable substrate, but our experience has led us to conclude that plated parts and air bearings are a poor combination as failure of the plating will destroy the bearing.

Having placed these constraints on ourselves, we studied the family of bronzes available to us. Tests were run using unlubricated samples of aluminum bronze and leaded bronze. The result of these experiments was that the bronzes were generally very forgiving of dry sliding contact, especially at low speeds. Based on this information

it was decided to use SAE 660 bronze for both the stationary and the moving parts of a small metrology spindle.

SPINDLE CONSTRUCTION

Figure 1 illustrates the construction of the spindle chosen for manufacture using diamond turning. The spindle has three main parts. The top part of the thrust bearing doubles as the table of the roundness gage. This part is made from stainless steel and is lapped to achieve flatness on the lower bearing surface. The outer part of the bearing is made from bronze and is about 140 mm in diameter and 35 mm thick. The lower part of the rotor is also of bronze and has a 57 mm diameter journal bearing as well as a 111 mm diameter thrust surface. Both of the bronze parts are diamond turned on all of their surfaces. Journal and thrust surfaces are maintained square within 0.5 microns, the thrust surfaces are machined flat within 0.5 microns, and the radial bearing is held round to within 0.5 micron FIM.

RESULTS

As the first few spindles were manufactured using the new techniques, it became apparent that, as expected, the error motion of these spindles was reduced to less than 20 nm. Some spindles exhibited error motions which were difficult to measure with the capacitance gage based spindle error analyzer normally used to qualify them.

In addition to improved accuracy, the new spindles could be manufactured more quickly than the older designs, and they were easier to assemble

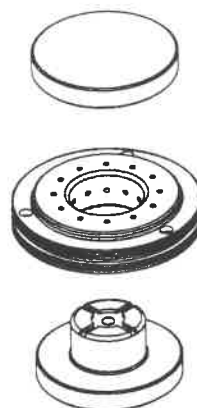


Figure 1: The spindle from a small roundness gage was the first application of diamond turning to air bearing manufacture.

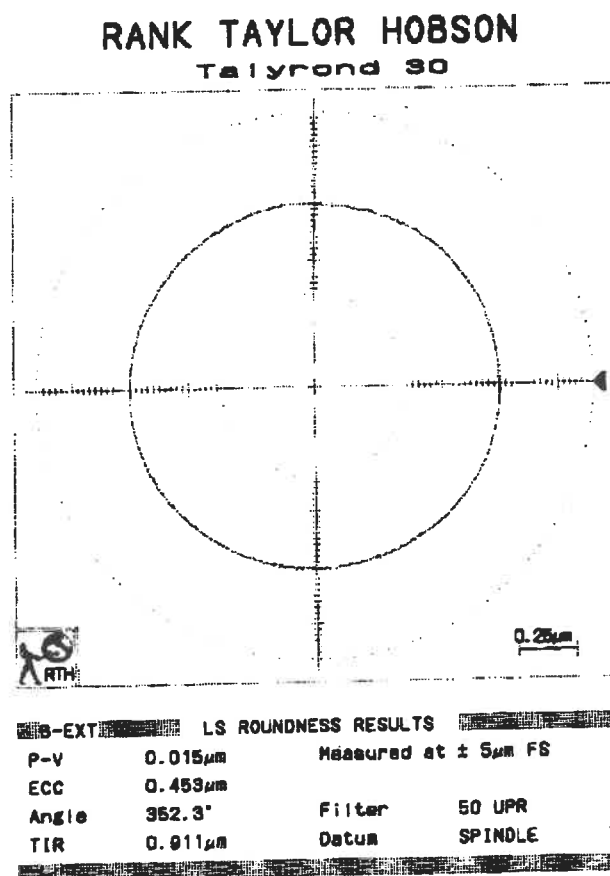


Figure 2: A roundness trace of a spindle with 15 nm total error motion.

because the parts fit better.

The results from the small spindle were so encouraging that the diamond turning method of manufacture has been applied to a similar spindle which is about 200 mm in diameter with much the same results as were achieved on the smaller spindle. Here the improved accuracy attainable has prompted us to look at smaller clearances and at alternative bearing designs including several orifice-less designs.

OTHER APPLICATIONS

Another example of using diamond turning to improve bearing performance concerns hydrostatic bearings. There are many different ways to design the devices which restrict the flow of liquid into the recesses of a hydrostatic bearing. Usually these restrictors are easily clogged and difficult to get to and clean. We have long looked for a device which would be resistant to dirt and could be removed from the spindle or slide for cleaning without requiring disassembly of the equipment. Diamond turning has proven to provide a way of designing such a device.

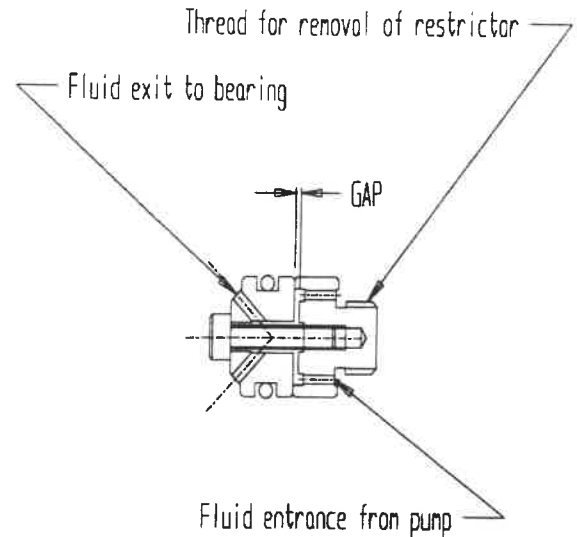


Figure 3: The hydrostatic restrictor is about the size of a pencil eraser and is meant to be inserted in a hole in the bearing assembly.

Figure 2 shows how the diamond turned restrictor is constructed. This device is about the size of the eraser on the end of a pencil. Because the volumetric flow through the device is a function of the gap cubed, the step in height between the two flat annular surfaces on the right-hand side of the gap must be very tightly controlled. The two surfaces must also be flat and parallel to one another. The mating surface on the left must be flat. Only a diamond turning machine can generate the required surface geometry, holding the step height to a tolerance of 0.5 microns, or about 1% of the gap.

In use, this device is inserted into a hole drilled in the hydrostatic bearing structure. The o ring prevents the fluid from passing around the restrictor, and the pressure drop through the device keeps it pressed firmly against a step in the hole. The male thread is used to withdraw the restrictor from the hole, should it need to be cleaned.

The material used for the restrictor parts was free cutting brass, although aluminum or bronze could have been used instead.

APPLICATIONS FOR DIAMOND TURNING MACHINES

It may be well to reiterate here the qualities of a typical diamond turning machine which

make it different from other machine tools.

- * The squareness of the two orthogonal axes is generally 0.2 to 1.0 arc second. This is between two and ten times better than a typical machine tool.
- * The straightness of travel can be as good as 0.1 microns over 300 mm. This infers the ability to generate very flat surfaces and good cylinders.
- * The spindle error motions can be as small as 20-50 nm. This is about an order of magnitude better than conventional machine tools and allows the turning or boring of particularly round parts.
- * The overall vibration levels on a diamond turning machine are vanishingly small compared with other machine tools allowing the generation of exceptionally good surface finish.
- * The accuracy with which the axes can be positioned can be as good as a few tens of nanometers. Accurate positioning allows the generation of accurate steps and other features which would be impossible to manufacture using conventional lathes.

SUMMARY

Although we usually think of diamond turning machines as being dedicated to the manufacture of metal optics and other contoured parts, these machines have a place in the manufacture of precision mechanical components. In fact, diamond turning machines make it possible to create mechanisms which would be impossible to manufacture without the use of these ultra high precision lathes.

1. John P. Schaefer, "Diamond Point Machined Snap-Together Optics", Proceedings from American Society for Precision Engineering 1991 Annual Conference, pp 70-73

Manufacturing Method for a Monolithic Spectrometer Containing Five Self-Aligned Optical Surfaces¹

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1. Introduction

The need to produce aspheric optics in a timely manner and the difficulty in testing these surfaces has prompted research in self-aligned and self-contained optical systems. Traditional self-aligned optics have consisted of two coaxial aspheric surfaces single point diamond turned in a single machining step. Using the method developed at Oak Ridge National Lab for the production of the monolithic spectrometer, multiple optical surfaces with intersecting axes can be manufactured in a few machining steps while maintaining a high degree of accuracy. This paper will discuss the manufacturing method by which a monolithic spectrometer was produced containing five aligned optical surfaces, two of which are off-axis aspheric surfaces.

2. Optical Design

Figure 1. shows the optical design and raytrace of the spectrometer. This device was designed to have a fiber optic input to the entrance surface. Light reflects off of the coated, parabolic collimating surface; a diffraction grating attached to or machined in the flat grating surface separates the component wavelengths of the beam; and a second aspheric surface focuses the separated rays onto the image surface. The axes of the two aspheric surfaces intersect to form a 39° angle. Raytracing software shows that the image produced by this device begins to deteriorate if the accuracy of the angular positioning varies by more than 0.25° or the displacement between surfaces varies by more than ± 10 microns. The spectrometer is designed to resolve 200nm/mm at the focal plane.

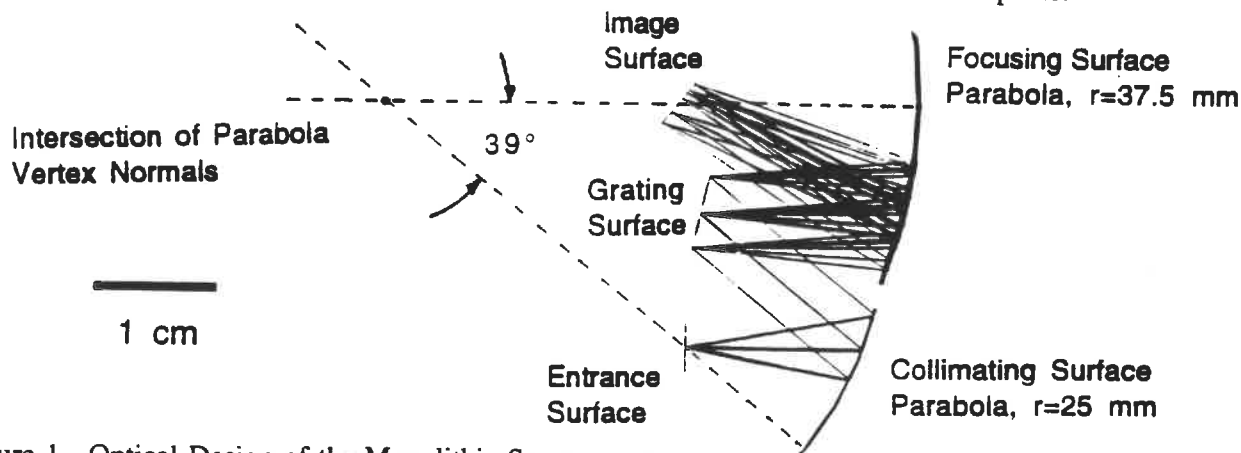


Figure 1. Optical Design of the Monolithic Spectrometer.

3. Manufacturing Process

The manufacturing process began by obtaining a cylinder of optical grade polymethyl methacrylate, PMMA. The outside diameter of this material was cut to a 90.00 mm diameter using a Rank-Pneumo Nanoform 600 diamond turning machine. Subsequently, a 39° wedge passing through the center of the cylinder was removed from the cylinder by a separate, diamond flycutting process. The substrate was then fixtured on the diamond turning machine, and the accuracy of the angle was verified to be within 1 minute of angle and centering was accomplished by diamond turning. The flat wedge surfaces are perpendicular to the axes of the aspheric surfaces, and the corner of the wedge will form the intersection of these axes. The wedge surfaces are parallel to the entrance and detector surfaces. The edge created by the flycut wedge passes through the intersection of the axes of the aspheric, or parabolic, surfaces. Figures 2 and 6 demonstrate the configuration of the substrate after this step.

¹Based on work performed at the Oak Ridge National Laboratory, managed for the U.S. Department of Energy under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

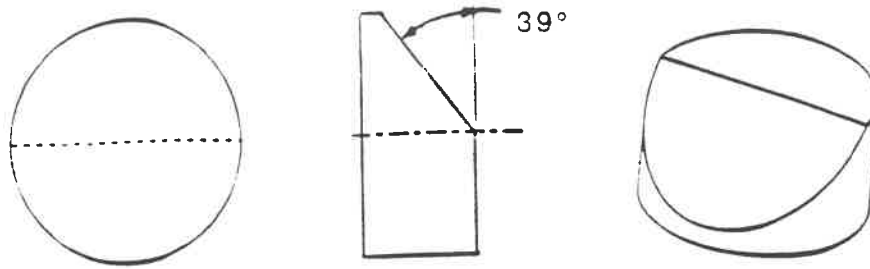


Figure 2. Cylinder with flycut wedge (top view, side cutaway view, oblique view).

The substrate is then vacuum fixtured on the base with the wedge removed. The cylinder surface is used to ensure that the center of rotation coincides with the center of the part. Three surfaces will be diamond turned in the substrate at this step. The first parabolic optical surface will be machined. A reference flat and positioning cylinder will be machined for mounting in a later step. Also, a sphere will be diamond turned to be used to center the substrate for machining the subsequent parabolic surface. The center of the sphere coincides with the intersection of the axes of the two parabolas. Figure 3. shows the configuration of the substrate at this step.

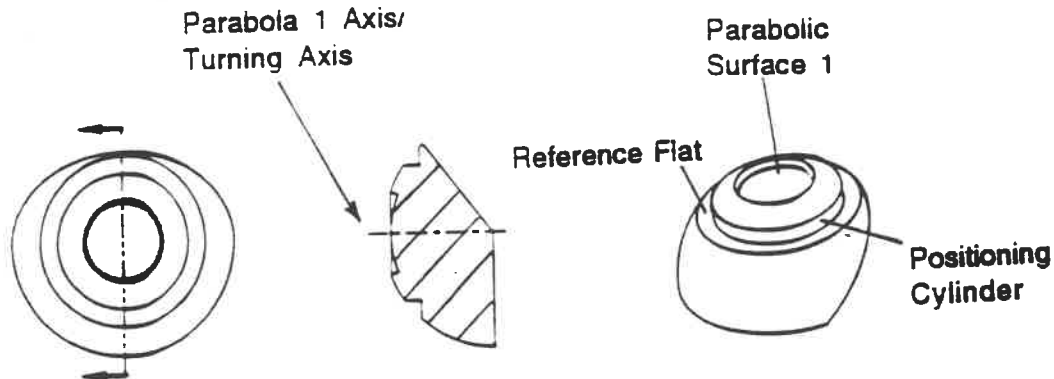


Figure 3. Substrate with reference sphere, parabolic surface, and mounting surfaces.

The substrate is now ready for the second aspheric surface, another parabola, to be machined. Due to careful preparation, the substrate can be tilted on the wedge shaped base, and centered on the vacuum fixture by probing the sphere machined in the previous step with a ruby-tipped, air-bearing, LVDT mounted on the diamond turning machine. The surfaces are positioned to within 1 micron concentricity as verified by the LVDT. A second reference flat, identical to the first one, is machined during this step to be used as a reference for future surfaces. Figure 4. shows the substrate after this manufacturing step.

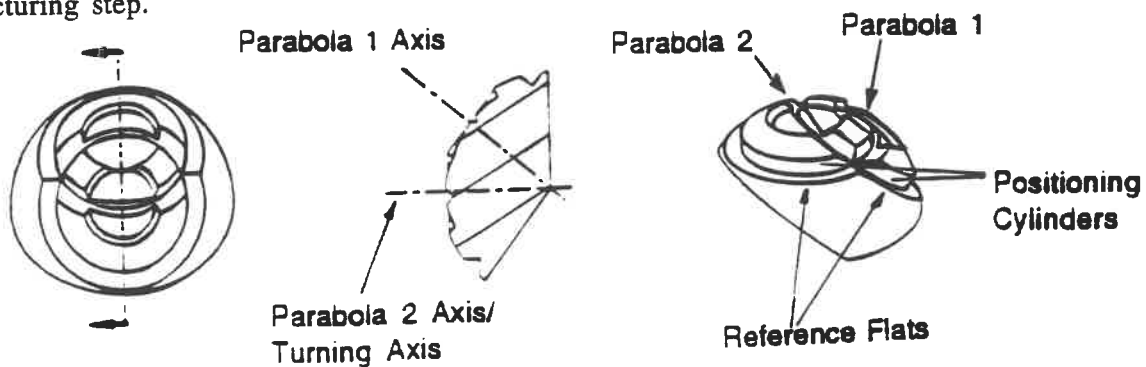


Figure 4. Spherical substrate after machining the second set of optical and mounting surfaces.

The substrate is now ready to be turned over and have the optical surfaces on the back side of the optic fabricated. The design of this optic was manipulated in such a manner as to yield the entrance surface and the detector surface normal to the axes of the opposing parabolic surfaces. This feature simplifies the fixturing required for this surface. Reference flats manufactured with the opposing parabolic surfaces allow for convenient fixturing of these surfaces. The reference surfaces were designed such that one fixture could be used to manufacture both the entrance and detector surfaces.

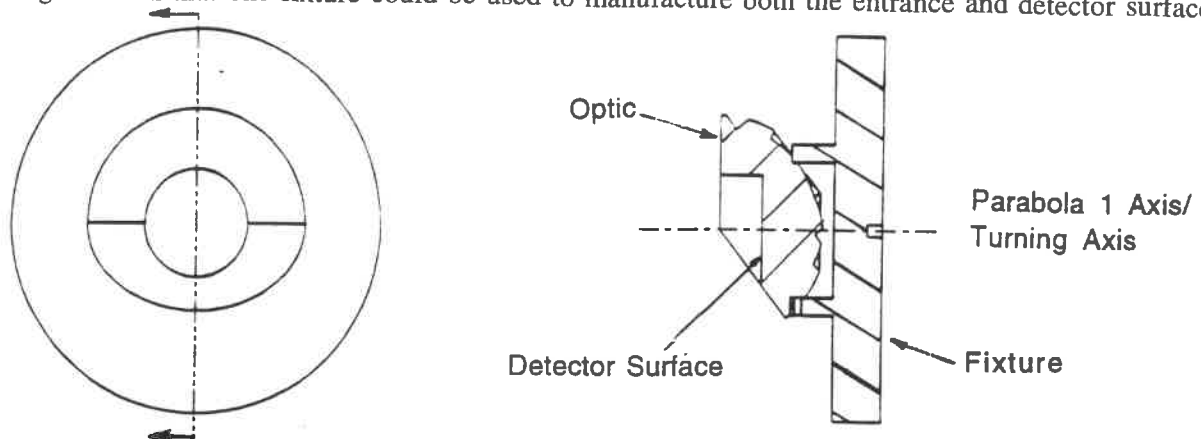


Figure 5. Substrate shown in fixture for machining the two optical flats on the back side of the substrate. The surface shown is the detector surface

The final diamond turning step is the fabrication of the diffraction grating surface. This surface is tilted with respect to the entrance axis of the optic, and required that a tilted fixture be developed to fabricate this surface. This fixture was the greatest source of error in the manufacturing process. Metrology showed that the fixture angle varied by 6 minutes or 0.10° from the desired angle. The edge created when cutting the entrance surface was used to reference clocking and depth of cut.

4. Assembly and Testing

After all of the optical surfaces are manufactured, a gold coating is applied to the aspheric optical surfaces due to their reflective application. A 300 line/mm diffraction grating was applied to the detector surface. An NEC linear (1024x1) CCD array was mounted to the detector surface. Alignment of the fiber optic input and CCD array was accomplished by knowledge of the proximity of the devices within a millimeter and adjustment for optimum output. An initial test was performed to ensure the operation of the device. After verification that the device was operational, the remaining substrate was removed by a milling operation to yield the small optical device (15x25x28mm) and the surfaces not required by the optical device were blackened to prevent unwanted reflections inside the optic.

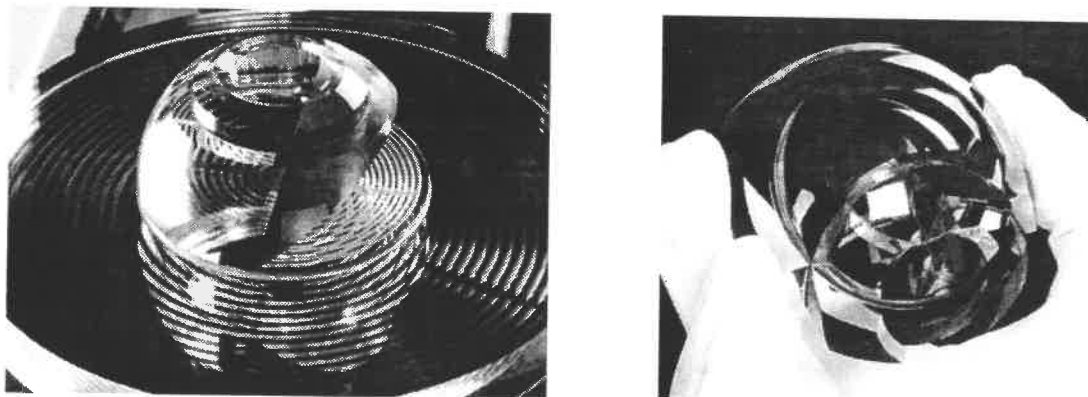


Figure 6. Left photo is of sphere and wedge substrate with first parabola machined. Right photo is of the handheld substrate with both parabolas. The area of reflection is that which has been gold coated, and gives an idea of the final size of the optic after unneeded references are removed.

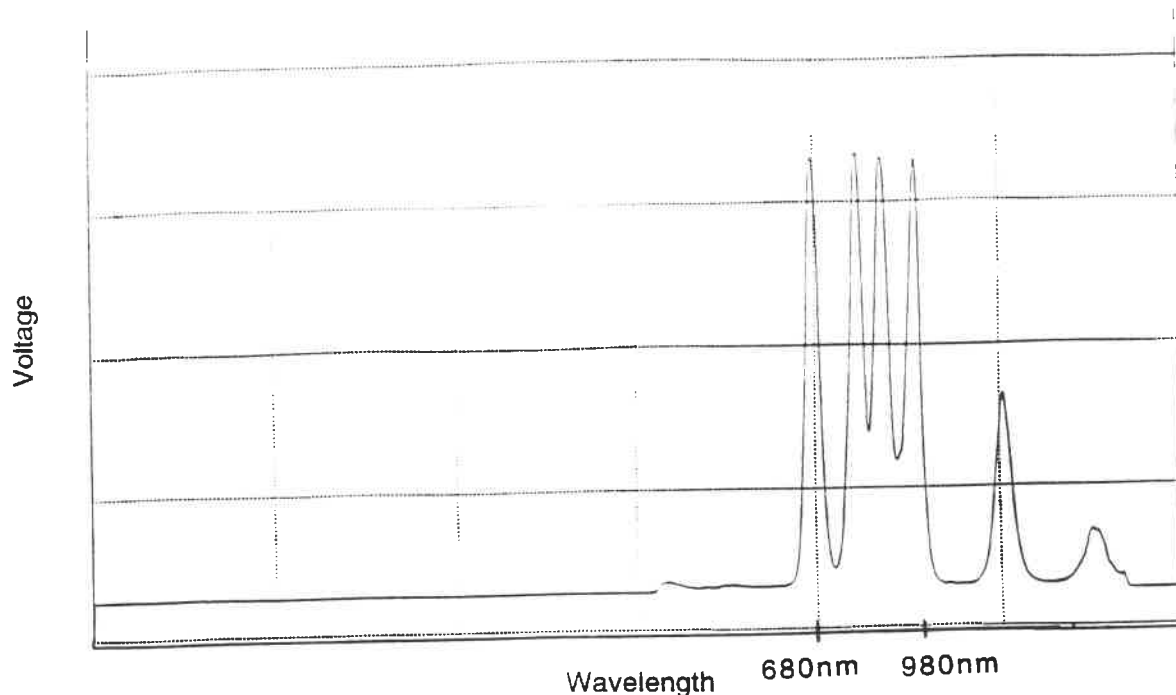


Figure 7. Output from the assembled scatterometer. The first four peaks on the left are the -1 order of 635nm, 780nm, 850nm, and 980nm. The last two peaks on the right are the second order 635nm and 780nm. The very small bump on the left is an indication of the noise level of the device.

5. Conclusions

When assembled, the optical device differentiated several peaks with excellent separation and low noise as shown above in figure 7. All of the surfaces manufactured in this procedure were referenced to each other using the diamond turning machine as a coordinate measuring machine. The major contribution of errors in this process were fixturing errors, which were measured using the Nanoform 600 as a coordinate measuring machine. Errors in positioning the substrate were within the measuring resolution of the air-bearing LVDT used for centering the substrate. The substrate was always positioned to within 1 micron concentricity with the turning axis of the diamond turning machine. Surfaces were located using a small cut of the diamond tool, and these surfaces were located to within 0.1 microns. The combination of the wedge surface and spherical surface allowed for easy alignment of the aspheric surfaces, although the substrate was tilted and remounted on the diamond turning machine between these steps. The later surfaces machined on the back side of the optic were produced to the same precision as those on the front.

3 Measurement of Array Coherence

Measurements are required of position in the five specified degrees of freedom of a grating array. To fulfil a wavefront criterion, diffracted wavefront observation is a standard instrumental technique using the Twyman-Green Interferometer with the grating set up as the test-object in the 'retrodiffractive' condition where the (diffracted) beam is returned along the reciprocal of the path of the incident beam as shown in Figure 1 (the 'Littrow' spectrometer arrangement). In the first diffracted order there is a one-wave path difference in the returned beam between the diffracted wavelets from successive grooves and the spatial coherence of the light source needs to exceed the delay between extreme rays of the grating aperture (readily satisfied by a laser). A pair of coplanar and perfect identical gratings may be maintained in phase by aligning and co-phasing fringe-patterns.

With a single wavelength (laser) source of long coherence, there are two special cases of motion which ambiguously permit aligned co-phased fringe-patterns when the gratings are parallel but not coplanar. With respect to a datum first grating, the second may be displaced laterally across the beam normal to the grooves, shown as motion X in Figure 2. Also, the second grating may be in a position along the optical axis an integer-number of half-waves ahead of or delayed with respect to the extended plane of the datum grating (motion Y in Figure 2). Unlike these, the allowable positions lie only in the extended datum grating plane.

Coplanarity can be ensured by a small aperture white-light interferometer aligned normal to the substrates and centred on the join between a pair of gratings (or the corners of four). Alignment of the central (achromatic) fringes in each and of corresponding neighbouring fringes signifies coplanarity. To monitor any form differential or distortion arising, it was found useful to employ a full aperture instrument, accessed by rotating the pair by a small angle so as to bring the zero (reflected) order into alignment with a plane mirror (and take the diffracted beam out of alignment).

4 Control of Array Coherence

Fine micrometer screws readily provide for adjustments of an optical element in pitch, yaw and translation. Combined with a tilt-stage to provide for roll adjustment and with a flexure-motion stage for in-plane translation normal to the grooves, a pair of 70mm wide 600 g/mm gratings were aligned using interferometers to monitor reflected and diffracted wavefronts. It was found useful to employ piezoelectric actuators compounded with the micrometer screws to provide for fine sub-micrometre adjustment in each degree of freedom.

Although both gratings were derived from the same master (itself a fused silica replica) and were on the same substrate material (Schott 'zerodur'), it was found that, soaked to the same temperature and set up to be coplanar within $1/10$ fringe as measured in the 'zero-order' (reflecting mode) interferometers, in the first diffracted order there was a one-third fringe slope difference in fringe patterns. Such a difference could have arisen

from a temperature difference during the replication process, leading to a progressive relative position-difference totalling 1/3rd of a groove-space between the *first and last* grooves across the widths of the gratings. Whereas in a monolithic grating a small constant deviation from the (specified) groove spacing is trivial, in the array a difference in groove spacing between elements, leading to more than about a 1/10 fringe slope difference in the diffracted interferograms, is not tolerable. It is anticipated that, with care, adequately repeatable replication could be achieved.

5 References

Harrison G R 1973 "The Diffraction Grating - an Opinionated Appraisal" App Opt vol12 pp2039-2049; see also the front cover of this particular journal-issue (Sept./pt.9) showing Dean Harrison with a 600mm grating.

Labeyrie A 1977 "Coherent Arrays" in Pacini F, Richter W and Wilson R N (eds) Proc Conf 'Optical Telescopes of the Future' ESO Geneva, Switzerland pp 375-388

6 Figures

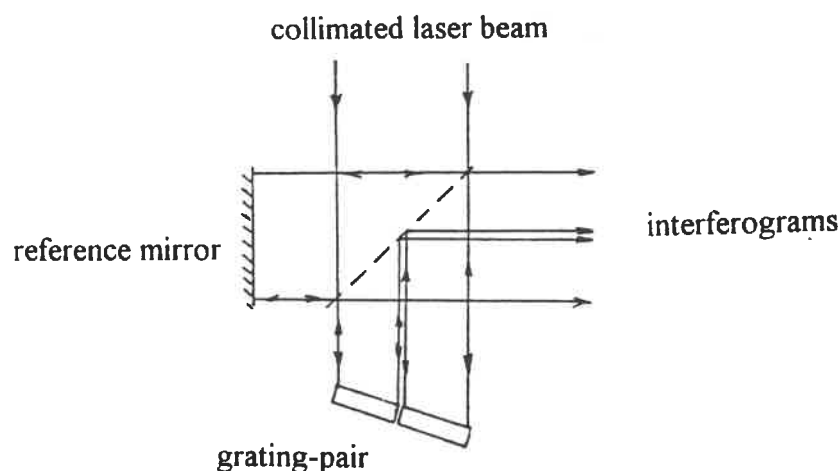


Figure 1. Gratings Monitored in First (Littrow) 'Retro-diffracted' Order Using a Twyman-Green Interferometer

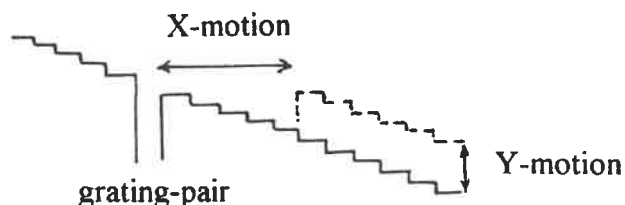


Figure 2. Position Ambiguities in Interferometric Alignment of Gratings Using a Long-coherence (laser) Light-source

Determination of Anisotropy in the In-Plane Radial Residual Stresses of 100 mm Diameter (100) P-Type Silicon Wafers by Shadow Moiré Interferometry and Finite Element Analysis

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In-plane radial residual stresses were determined from the out-of plane deflections of 100 mm diameter (100) p-type silicon substrates. 100 mm diameter substrates, supported on the knife edge, were bent under a centro-symmetric load and the out-of plane deflection of the wafers was measured as a function of the applied load. For a given wafer and center-symmetric load, tensile in-plane radial residual stresses reduce the amount of out-of plane deflection. On the other hand, compressive in-plane radial residual stresses increase the amount of the out-of plane deflection for a given load. Hence, the magnitude and sign of the in-plane residual stresses were related to the out-of-plane deflection of the substrates.

The out-of plane deflections of the wafers were measured experimentally by Shadow moiré interferometry. Shadow moiré is an easy and convenient technique for in-situ measurements. While Shadow moiré is easy to implement, it has also the capability of providing a large amount of information in one interferogram, thus, is especially advantageous for capturing spatial variations in large areas.

A Shadow moiré setup combined with an image processing/data acquisition system were used to determine the out-of-plane deflection of the wafers. For a given point on the moiré pattern captured by a newvcon tube camera, the spacing and density of the interference lines (which appeared as concentric circles for our geometry) were related to the amount of out-of-plane deflection. An image processing software was used to locate and measure the spacing between the dark and bright areas. A spread sheet was used to convert the experimental and geometrical parameters to actual deflection measurements.

Previous work has shown that a relationship between the out-of-plane deflections and the in-plane radial residual stresses can be obtained from Timoshenko's theory of thin shells as applied to the bending of a circular single crystal substrate. This work has been modified to produce the relationship between the amount of out-of-plane bending for a given load (applied at the center) to the in-plane radial residual stress for a large area--wafer by comparing the hypothetical stress-free deflections to the actual measured deflections.

A finite element model was used to verify the out-of-plane deflections and account for the anisotropy expected in the defalcation of single crystals. This numerical model was capable of accounting for the variations in the Young's modulus and Poisson's ratio by using the actual compliance tensor. This allowed the model to account for the errors and approximations in the material properties due to averaging.

This numerical model was used to verify the deflection behavior of a stress-free single crystal silicon wafer. Since the stress formulation relates the actual measured deflections to the hypothetical stress-free deflections, the accuracy of the determination of the in-plane radial residual stresses depends on the accuracy in the prediction of the bending of

the stress-free wafer. The deflection readings of the numerical model was used to verify the predictions by the analytical model for the stress-free single crystal substrate. The comparison of the analytical and numerical results verified the stress-strain analysis and the effects of material anisotropy in the in-plane radial residual stresses. The spatial variation of stresses as a function of position on the wafers were represented in maps of stress magnitude and sign. In-plane radial residual stresses could be as high as 5 MPa (compressive) at the center, and decrease to zero at the edges as expected. Bending of 100 mm diameter (100) p-type single crystal silicon substrates can be approximated by using the average Young's modulus and Poisson ratio.

Part Transfer in Ultraprecision Machining Processes

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The manufacture of high precision parts often involves more than a single set-up or fixture. Here the part that is transferred between the different fixtures can affect the accuracy of the finished part. An example of this type of process is the machining of a thin walled stainless steel spherical shell. The outer surface of the shell is machined first and then the part is moved to a pot-like fixture where the inner surface is machined. The fit, or registering, of the part in the second fixture directly affects the wall thickness accuracy -- an important dimension in this case.

For a manually controlled procedure, a skilled operator can develop a "feel" for the fit of the part in the fixture; however, when we move toward automating the operation it is necessary to have a more easily controlled process. By switching from the force controlled operation of the skilled operator to a displacement controlled method using an ultraprecision machine, we can use a precision engineering error-budget approach to design the controlled process.

The precision engineering approach was used to design the part transfer scheme for manufacturing stainless steel shells as one of the applications of the Precision Automated Turning System. This design approach lead to an integral transfer system that has dictated some of the basic design features of the entire system. The transfer alignment requirement used for this design is 3 micrometers, even though the tightest tolerance on the part is 25 micrometers -- a case where micrometer level precision is needed in the manufacturing process of a large part with conventional tolerances.

Multi—dimension Inspection Technology in Quality Management

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1. Introduction

With the development of the market economy, product quality is becoming more and more important. The precision of measurement and the degree of automation becomes higher. Moreover, the range of measured variables is expanding, especially in the project of inspecting many dimensions of axle—kind components on—line. In this case, many sensors are needed to measure simultaneously, then correlated dimensions are analysed. Some complicated dimensions or form—position dimensions can be measured by this method.

Computer Aided Quality Control (CAQC) is a dispensible part of Computer Integrated Manufacturing System (CIMS). The Quality Assurance System (QAS) is a project that many researchers are working on. It is a good idea to develop a measurement instrument which has SPC functions and network interface. The users can operate this instrument on sites to inspect process quality. This is very convenient and valuable.

2. The Structure of ZK—5 Type Inductance—style Quality Management Instrument

In order to measure many dimensions at one time, we develop a ZK—5 type multi—channel inductance—style measurement and quality management instrument. The hardware of this instrument consists of sensor signal amplifier, A/D, MCS—8098 digital part, D/A, I/O and micro—printer with a MCS—8031 microprocessor system. The sensor signal amplifier is made up of balanced bridge, sine—wave oscillator, preamplifier, phase—sensitive detector, electric filter and emitter—follower, etc. The hardware structural chart of instrument is shown in Fig. 1.

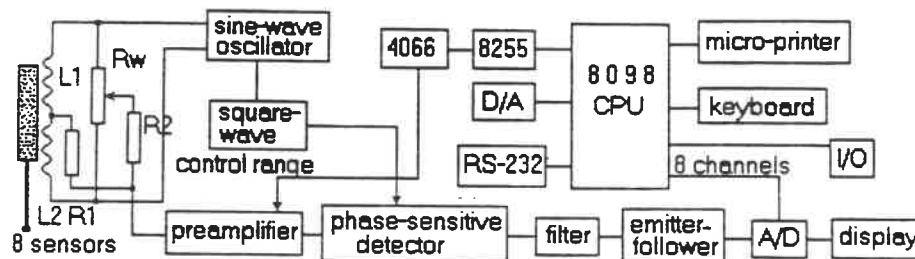


Fig. 1 The hardware structure of ZK—5 type instrument

As shown in Fig. 1, sine—wave oscillation is imposed on the coils L1, L2 of the inductance sensor and the variable—resistance Rw. The variation of the displacement of the sensor is changed

into the variation of voltage proportionally. 8098 CPU samples this voltage and measures out the dimensions of components. CPU samples 8-channel voltages in turns through switch 4051. The necessary time for one sensor measurement including sampling three times and then calculating is $42\mu s \times 6 + 5\mu s = 3\mu s$. The time for all eight sensors measuring out is about 2.5ms ($302\mu s \times 8$). This speed can meet the need of on-line, real-time inspection.

In order to utilize the goodness of 8098 CPU, the selection of measurement range and channels is automatic. Through the authors' experiments, the zero-drift and non-linearity of this instrument are compensated by software methods. The measurement range is $\pm 400\mu m$. The highest measurement precision is $\pm 0.2\mu m$.

3. The Principle of Multi-dimension Inspection System

With one sensor, one dimension can be measured. If many sensors are used simultaneously, many dimensions can be measured by multi-dimension inspection technology. Moreover, the complicated dimensions or form-position dimensions can be measured by further calculation.

The principle of multi-dimension inspection is shown in Fig. 2, 3, 4. In Fig. 2, the measured results from sensor #1, #5 and the results from sensor #2, #6 are added respectively to get the diameters of step-axle. Sensor #3 measures the axial run-out. In Fig. 3 the result of sensor #1 subtracts the result of sensor #5, then the perpendicularity between the axis of the pin-hole and AB axis by further calculation. In Fig. 4 sensors #1, #2, #3, #5, #6, #7 measure out the longitudinal profile of the skirt part of piston.

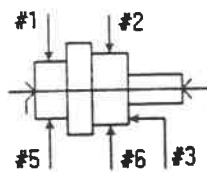


Fig. 2 combined measurement for step-axle component

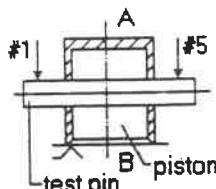


Fig. 3 perpendicularity measurement

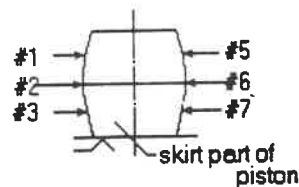
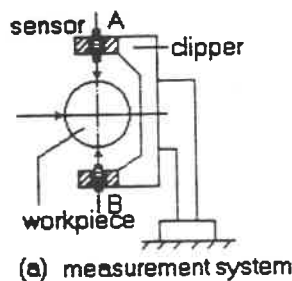
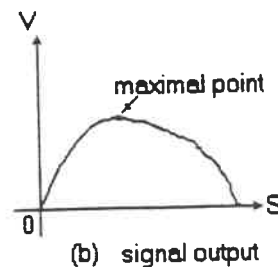


Fig. 4 longitudinal profile measurement

In order to measure the dimensions of axle-kind components, a clipper which can hold eight sensors and measure automatically is designed specifically. ZK-5 type instrument continuously compares the sampled data of one channel, as shown in Fig. 5. When the sensor A and B move from the left of the component to the right of the component, there must be a maximal value in one position. This maximum is the diameter of this component.



(a) measurement system



(b) signal output

Fig. 5 principle of automatical measurement

4. Axle-kind Components Multi-dimension Inspection "Island"

Two main demands are presented by the development of manufacturing automation: first, the manufacturing system must be suitable for complex and variable processing and products; second, the system must have higher reliability and stability. CIMS is suitable for these two demands. The machinery manufacturing technique, computer hardware and software technique, quality engineering and management technique are all integrated in CIMS. SPC controllers and ZK-5 type measurement and quality management instrument just control the quality of individual processes. How to make these instruments form a Local Area Network (LAN) so as to assure the whole product quality is an important project. Moreover, this LAN is connected with the whole product quality is a important project. Moreover, this LAN is connected with the internal standard net in CIMS. Here, the hierarchical quality control method is adopted. By this means, ZK-5 type instrument and other controllers can construct a Axle-kind Components Quality Inspection "Island" (ACQII). As shown in Fig. 6, this inspection system consists of ZK-5 type instrument, clipper, robots and feedback controller, etc.

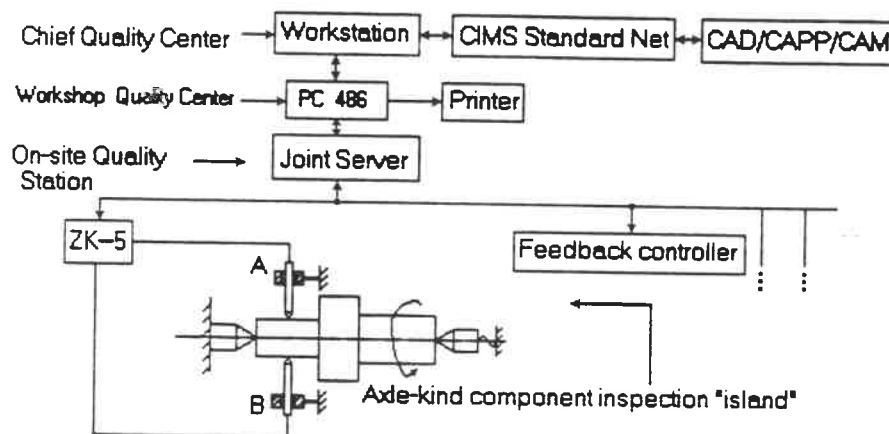


Fig. 6 axle-kind components inspection "island" structure

At first, ZK-5 type instrument saves the measured data. When necessary, it can make Statistical Process Control (SPC) analysis with sampled data, then prints out the analytical results including data and figures. It can also forecast real-timely using time-series modelling. The instrument transmits the measured data, component code, process code, component designed dimensions and tolerances to supervisory computers such as PC 486. The further analysis is executed in the supervisory computers and the results are feedbacked to controllers to control the process quality.

5. Correlation Analysis of Multi-dimension Inspection

In two or more than two correlated processes, the correlation analysis is needed. The simplest

means is the linear correlation analysis (non-linear correlation can be changed into linear correlation). The degree of correlation is demonstrated by the coefficient r , ($|r| \leq 1$).

With respect to 2 correlated N sampled data series X and Y :

$$|r| = \frac{(1/n) \sum_{k=1}^n (\bar{x} - x_k) \times (\bar{y} - y_k)}{N \times \alpha_x \times \alpha_y}, \quad \alpha_x, \alpha_y \text{ are variation of } x, y, \quad k=1 \sim n;$$

The purpose of correlation analysis is to find out whether there is correlation among many processes or not. It can decide if there is correlativity between raw process and fine process so as to find out the reasons of errors.

Follows is an example to analyse the relation between internal ring dimension in raw and fine grinding process in the final internal centerless grinding process of the internal ring bearing.

As shown in Fig. 7, sensor A and B measure out the dimension X of internal ring in raw grinding process and dimension Y of internal ring in fine grinding process. The correlation analysis with measured data X and Y demonstrate that $|r|$ is near to 1. So there is a very close correlativity between internal ring dimensions in raw grinding process and in fine grinding process.

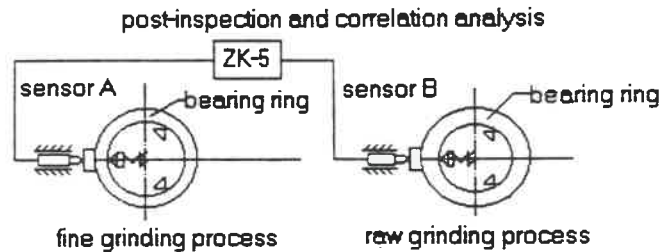


Fig. 7 correlation inspection in the final internal centerless grinding process of the internal ring bearing.

6. Acknowledgement

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